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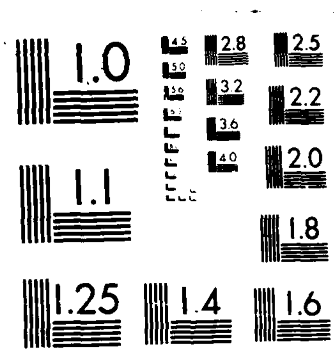

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This report describes work to date on the subject contract, a book on "Combustion Instability in Solid Rocket Motors". The report includes a brief introduction on the purpose of the book and a summary of progress to date. An Appendix describes a computerized bibliographical system set up for the project, including subject coding. Another Appendix provides the current outline of the book, and a third Appendix contains the first three chapters and part of the fourth chapter.

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AFOSR-TR- 87-0459

TECHNICAL REPORT ON
AFOSR CONTRACT F49620-86-C-0005
23 February 1987

E. W. Price
G. A. Flandro

COMBUSTION INSTABILITY IN SOLID PROPELLANT ROCKETS

Introduction

This project concerns assembly, synthesis and comprehensive presentation of information on combustion instability in solid rockets, in the form of a reference book. The format is chosen to make the book suitable for a wide audience of readers including propulsion program managers, motor designers, propellant chemists, test engineers, and combustion specialists. The diversity of audience is accommodated by opening with general introductory chapters for nonspecialists, with progression into more intensive theoretical treatment in Chapters 5 - 11. Chapters 12 - 14 are on more applied issues, such as experimental methods and remedial measures. All chapters open with Introductions that give a relatively non-technical statement of the problem and content, and end with a qualitative summary of what was done in the chapter. An extensive bibliography is included, and supplemented by a more complete, computer-based bibliography with search-retrieval capability.

Progress

A library of reference materials has been assembled and extensive review has been made (and continues as needed during preparation of text). The computerized bibliographical search program has been finished, and computer disks with partial data base were forwarded on 30 November 1986. Subject coding and data base entries are continuing. The subject code in use is shown in Appendix A, along with a sample entry and a copy of the menu for computer operations. A user's manual has been prepared.

87 4

Development of the outline of the text has continued, working toward a) improved connectedness and continuity, b) more complete coverage of the subject matter, and c) updating to accommodate new research. The latest version of the Outline is shown in Appendix B.

Chapters 1 - 3 are completed except for art work and some bibliographical material, and are enclosed as Appendix C. Also included is about 70% of Chapter 4, which was completed earlier and then set aside following a decision to substantially enlarge the chapter [This chapter presents the general background on how propellants burn, and must necessarily represent a drastic condensation of a vast literature. It was decided that the first version was too superficial for adequate understanding of the realities of the oscillatory combustion problem to be discussed in the subsequent chapters]. Extensive writing has been done on the rest of the chapters, particularly Chapters 5 - 11.

Computer graphics equipment has now been obtained for preparation of manuscript art, and a graduate assistant has been assigned to this activity. The extent of completed text to date is less than anticipated, but the effort has been distributed over most chapters as opposed to sequential work on chapters, and the very time-consuming literature assembly and review has been substantially completed on all chapters. It is anticipated that the text will be completed on schedule and the bibliography ahead of schedule. Illustrative material (final art) has not progressed far enough to estimate schedule, but work is now started and rate of progress will be established shortly.

APPENDIX A

Information on Bibliographical Computer Software

COMBUSTION INSTABILITY

SUBJECT CODE LIST

<u>Combustion</u>

1. Analytical
2. Experimental
3. Combination

<u>Fluid Dynamics</u>

4. Analytical
5. Experimental
6. Combination

<u>Combustion-Flow Interaction</u>

7. Analytical
8. Experimental
9. Combination

<u>Stability</u>

10. Analytical
11. Experimental
12. Combination

<u>Materials</u>

13.

<u>History and Motor Case History</u>

14.

b.lst

SAMPLE BIBLIOGRAPHICAL ENTRY

EDITING ENTRIES RECORD NUMBER 26

SERIAL # 26

SUBJECT CODING(S) 4 7

TITLE Investigations of Reactive and Non Reactive Acoustic Boundary Layers i
n Porous Wall Ducts

AUTHOR #1 LAST NAME	Hegde	FIRST & MIDDLE INITIAL	U. G.
AUTHOR #2 LAST NAME	Chen	FIRST & MIDDLE INITIAL	F. L.
AUTHOR #3 LAST NAME	Zinn	FIRST & MIDDLE INITIAL	B. T.
AUTHOR #4 LAST NAME		FIRST & MIDDLE INITIAL	

REPORT NUMBER CPIA Pub. 412
DATE OF PUBLICATION 10/04/84

SOURCE Chemical Propulsion Information Agency, Laurel, MD, 21st JANNAF Combu
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CURSOR MOVEMENT -Up, Down, Left, and Right arrow keys
INSERT MODE -Ins (toggles) PREVIOUS/NEXT RECORD - PgUp, PgDn
DELETE CHARACTER -Del DONE -(control)End

MAIN MENU SCREEN

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* * * * MAIN MENU * * * *

1)   ADD ENTRIES
2)   EDIT ENTRIES
3)   SEARCH ENTRIES
4)   LIST OF SUBJECT CODES
5)   DELETE ENTRIES

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PICK A NUMBER OR TYPE Q TO QUIT.
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APPENDIX B

Outline of Text as of 2/20/1987

COMBUSTION INSTABILITY
IN SOLID PROPELLANT ROCKET MOTORS

4.0 Fundamentals of Propellant Combustion

- 4.1 Introduction
- 4.2 Nature of Propellants and Ingredients
- 4.3 Ingredient Decomposition and Self-Deflagration
- 4.4 General Features of Propellant Combustion
- 4.5 Analytical modeling program - steady state
- 4.6 General Nature of the Dynamic Response of Combustion

5.0 Analytical Modeling of Combustion Dynamics

- 5.1 Introduction
- 5.2 Decisions regarding completeness of models
- 5.3 Inherent time constants
- 5.4 Classical 1-D model (thin combustion zone)
- 5.5 Multiple flame, statistical models
- 5.6 Limitations of models

6.0 Analytical Modeling of Combustor Flow

- 6.1 Introduction

- 6.2 Description of combustor flow
  - 6.2.1 Need for detailed description of flow field
  - 6.2.2 Typical mean flow patterns in simple geometries
  - 6.2.3 Effects of real motor port features on mean flow
  - 6.2.4 Flow at burning surface
  - 6.2.5 Flow at inert surfaces
  - 6.2.6 Flow at nozzle entrance
  - 6.2.7 Separation of steady and unsteady flow components
  - 6.2.8 Nonlinear interactions such as convective coupling
  - 6.2.9 Applicability of continuum ideal gas models

6.3 Decisions regarding completeness of models

6.3.1 Assumptions made in modeling of mean flow field

6.3.2 Assumptions made in modeling of unsteady flows

6.3.3 Limitations of resulting flow models

6.3.4 Description of analytical bases for current models

6.3.5 Recent evidence of inapplicability of assumptions

6.3.6 Selection of models to be described

6.3.7 Need for improved models

6.4 Conservation equations describing rocket motor flow

6.4.1 Continuity

6.4.2 Momentum (Full Navier Stokes)

6.4.3 Energy (Complete time-dependent statement)

6.4.4 Equation of state (applicability of ideal gas)

6.4.5 Auxiliary relationships (two-phase flow equations)

6.4.6 Model No. 1 - irrotational, inviscid, ideal gas, no particles

6.4.7 Model No. 2 - rotational, inviscid, ideal gas, no particles

6.4.8 Model No. 3 - irrotational, viscous, ideal gas, no particles

6.4.9 Model No. 4 - irrotational, inviscid, two-phase flow

6.4.10 Other possible formulations and applications

6.4.11 Means for accounting for shear layer instabilities

6.5 Simplification of formulations by means of perturbation methods

6.5.1 Philosophy of asymptotic expansion methods

6.5.2 Benefits of linearization of equation sets

6.5.3 Linearized versions of the Model formulations

6.5.4 Retention of higher order terms, nonlinear effects

6.5.5 Application of energy balance methods

6.5.6 Interactions between mean flow and fluctuations

6.5.7 Inclusion of both hydrodynamic and acoustic terms

6.5.8 Inclusion of particle effects in perturbed equation sets

8.6 Analytical solutions for simple geometries (linear)

8.6.1 Usefulness of simple example solutions

8.6.2 Solutions for end burning grain

8.6.3 Longitudinal waves in tubular grain

8.6.4 Transverse modes in tubular grain

8.6.5 L* instability

8.6.6 Alternate methods of solution, energy balance methods

8.7 Outstanding problems of analysis

8.7.1 Failure of analysis in predictive mode

8.7.2 Sources of error

8.7.3 Flow turning effects

8.7.4 Velocity coupling

8.7.5 Turbulent mean flow effects

8.7.6 Mean pressure excursion problem

8.7.7 Interactions with surface erosion effects - secondary flows

8.7.8 Nonlinear effects

8.7.9 External vibration caused by combustion oscillations

9.0 Combustor Stability Computation

9.1 Introduction

9.2 Approaches and limitations

9.2.1 Selection of analytical formulation

9.2.2 Selection of simplifying assumptions

9.2.3 Selection of method of solution

9.2.4 Separation of acoustic mode determination from gain/loss calculations

9.2.5 Selection of time-dependent combustion representation

9.2.6 Inherent limitations of resulting model

9.7 Existing computer programs

- 9.7.1 Tabular listing of available programs
- 9.7.2 Description of operation of available programs
- 9.7.3 Nature of input data requirements
- 9.7.4 Form of calculation output
- 9.7.5 Example applications
- 9.7.6 Correspondence to experimental results
- 9.7.7 Sources of limitations of existing codes
- 9.7.8 Possible procedures for improvement of programs

9.8 Assessment of present analytical tools

- 9.8.1 Case histories
- 9.8.2 Failures and successes of existing programs
- 9.8.3 Suggestions for future improvements

10.0 Nonlinearities in Instability

10.1 Introduction

10.2 Kinds of nonlinear behavior

- 10.2.1 Evidence of nonlinear effects
- 10.2.2 The mean pressure excursion
- 10.2.3 Shock waves in finite amplitude longitudinal instability
- 10.2.4 Velocity coupling - a nonlinear phenomenon?
- 10.2.5 Mode coupling
- 10.2.6 Limit cycle behavior
- 10.2.7 True nonlinear instability
- 10.2.8 Generation of secondary flows - acoustic streaming
- 10.2.9 Shear wave generation and nonlinear distortion of acoustic modal structure

10.3 Status of understanding

10.3.1 Unresolved issues

10.3.2 Areas of disagreement between investigators

10.3.3 Assessment of experimental findings

10.3.4 Suggestions for resolving uncertainties

10.4 Modeling of nonlinear gas dynamics

10.4.1 Techniques for modeling nonlinear effects

10.4.2 Retention of additional terms in perturbation analyses

10.4.3 Models based on mode coupling

10.4.4 Models based on energy balance effects

10.4.5 Application of numerical solutions - status report

10.5 Modeling of nonlinear combustion response

10.5.1 What effects must be treated in nonlinear form?

10.5.2 Are multidimensional models necessary

10.5.3 Is the quasisteady assumption valid in nonlinear modeling?

10.5.4 Is velocity coupling an inherently nonlinear combustion response effect?

10.5.5 Status of analytical and computational modeling

10.5.6 Suggestions for improving the state of the art

10.6 Computation of wave behavior

10.6.1 Mode coupling effects

10.6.2 Representation of traveling steep wave fronts by superposition of standing acoustic modes

10.6.3 Application of the frozen waveform assumption

10.6.4 Status of numerical computations of nonlinear wave behavior

10.6.5 Comparison of computational results to experimental data

10.7 Stability thresholds

10.7.1 Observational origins of the stability threshold concept

10.7.2 Relationship to current models of nonlinear instability

10.7.3 Unresolved issues

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APPENDIX C

Chapters 1 - 3

and Chapter 4 (approximately 70% complete)

COMBUSTION INSTABILITY IN SOLID PROPELLANT ROCKETS

E. W. Price
G. A. Flandro
Georgia Institute of Technology

Chapter 1

INTRODUCTION TO COMBUSTION INSTABILITY

1.1 Introduction

High capacity combustors such as those used in jet propulsion systems are supposed to give smooth combustion at some design level determined by fuel-flow settings or design. However, such high energy systems sometimes operate instead spontaneously in an oscillatory fashion, with gas flow and combustion processes interacting periodically to produce severe pressure oscillations. Unless the combustor is specially designed for such conditions, it can be destroyed by pressure excesses, severe heating, or vibration-induced mechanical failures. Even if outright destruction does not occur, the oscillations can induce a variety of malfunctions in the flight vehicle.

Oscillatory modes of operation, while not ordinarily desired, are completely natural. If unwanted, their avoidance may require overt design consideration or experimental evaluation, and failure to do so often causes serious delays and costs in development programs for new propulsion systems. However, the physiochemical processes involved in nonsteady combustion-flow systems are very complex and "overt design considerations" mentioned above are by no means straightforward. Indeed, the relevant technical literature is very abstruse, as are the experimental strategies. While the practical problem has stimulated considerable research, the results are not usually effectively applied to system design until unacceptable oscillatory behavior is encountered in prototype or production systems. This tardy application of the available knowledge severely limits its utility because of the many commitments already made to design, and the high cost of making changes to control oscillatory behavior.

In the case of solid propellant rocket motors, the body of research is quite respectable, but poorly used because documentation of results is in the fragmentary form of several hundred research publications. In addition, the encounters with oscillatory combustion in development programs are so poorly documented that the seriousness of the problem is often underrated. The purpose of this report is to consolidate the research results and development program

experiences in a manner that makes the results more accessible and more easily understood. The manner of presentation is designed to serve the needs of a wide spectrum of readers.

1.2 Elementary Aspects of Oscillatory Combustion

The normal function of a solid rocket motor is to produce a controlled flow of high pressure, high temperature gas and accelerate it through a nozzle, thus producing thrust. The source of the hot gas is a solid propellant charge, and generation of the gas is accomplished by combustion of the solid at its exposed surfaces. The pressure is maintained by a balance between the rate of formation of gas by combustion and the rate of discharge through the nozzle. The formation rate depends on the area of exposed propellant, and the surface burning characteristics of the solid propellant. Prediction of mass rate is complicated by the fact that the propellant burning rate is dependent on pressure and other features of the gas flow environment. This complicates design somewhat, but is accommodated in conventional "internal ballistics" theory (Ref. 1.1-1.4). Such theory is based on steady state descriptions of combustor and nozzle flow, which are used as the basis for design of the propellant charge and nozzle. The dependence of the burning rate of each propellant (i.e., regression of the burning surface into the solid) on pressure and other variables is determined by separate "ballistic" tests, of which the simplest is the "strand burner" method (Ref. 1.5-1.7) for determining pressure dependence (it should be understood that any propellant is useful only if it has predictable burning rate, and that preparation procedures must be capable of making reproducible "batches"). Figure 1.1 shows a motor of very elementary configuration, in which the burning surface and gas flow are indicated, along with typical spatial distribution of pressure, velocity, and mass flow rates. Figure 1.2 shows some examples of experimentally determined burning rate over a range of pressure and propellant temperature.

The design procedures of internal ballistics do not take into account what would happen if there were a disturbance of the equilibrium between mass burning rate and nozzle discharge rate. The internal ballistics equations and laboratory burning rate measurements are based on steady state behavior. Those relations suggest (Fig. 1.3) that, if the pressure were for some reason off of equilibrium,

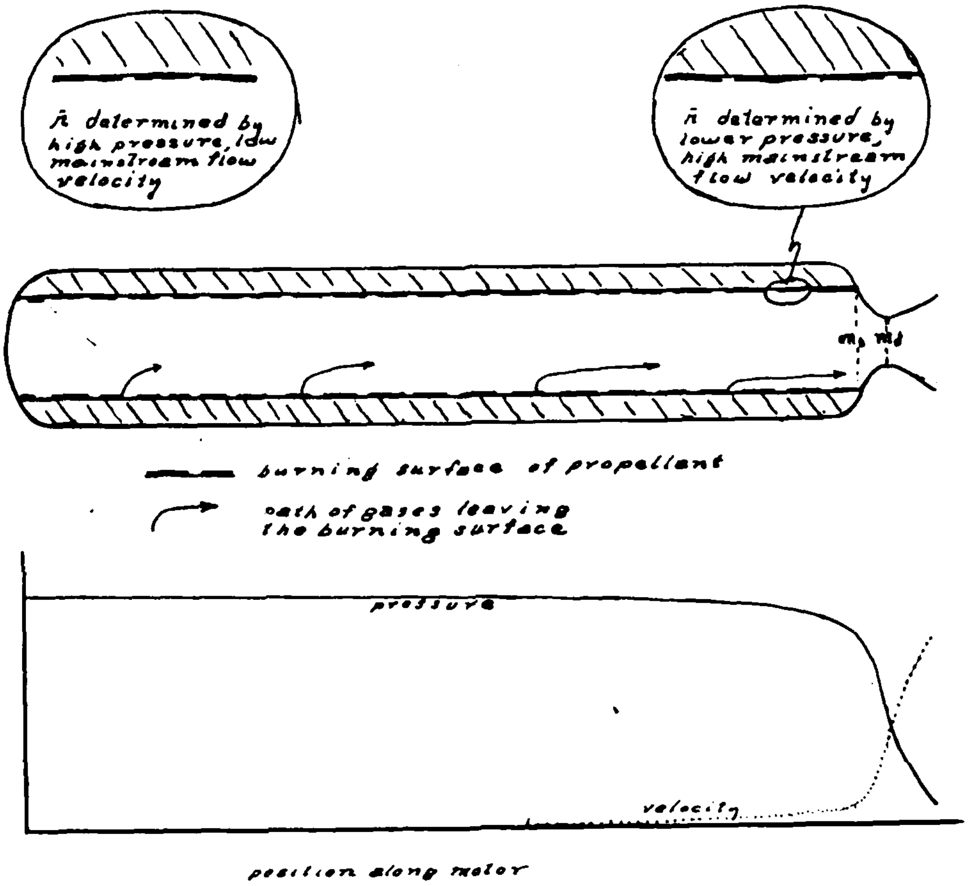

Fig. 1.1 Sketch of a combustor, showing location of burning surface and orientation of gas flow (top), and variation of pressure and mean axial flow velocity with axial location (bottom).

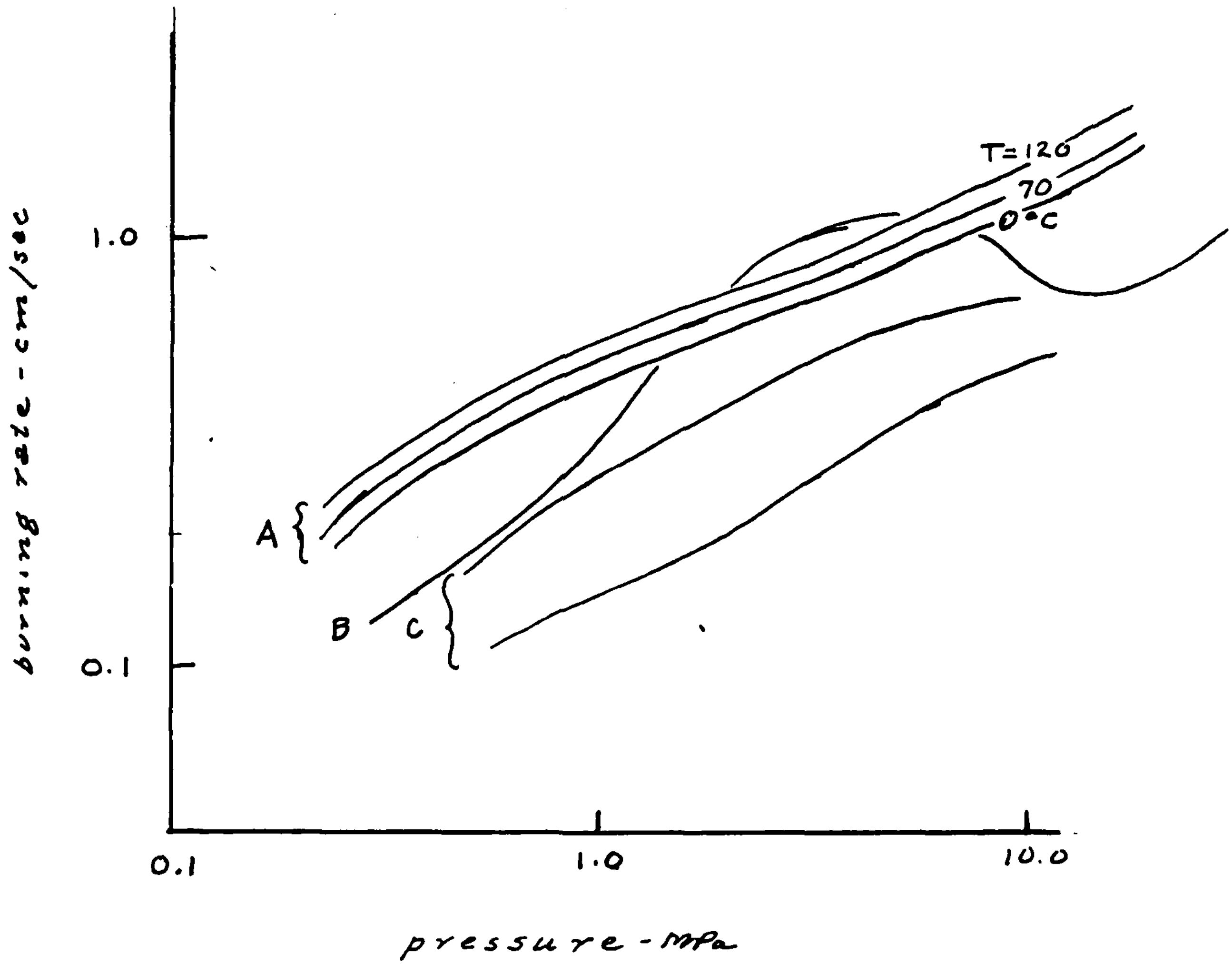

Fig. 1.2 Burning rate of propellant strands, as measured in a constant-pressure "strand burner". Curves a indicate typical dependence of rate on pressure at three different propellant temperatures. Curves b show the rate for a double base propellant with a catalyst that produces enhanced rate at low pressures and a desirably low or negative dependence of rate on pressure at motor design pressure. Curves c show the effect of oxidizer particle size on burning rate of an ammonium perchlorate-HTPB binder propellant.

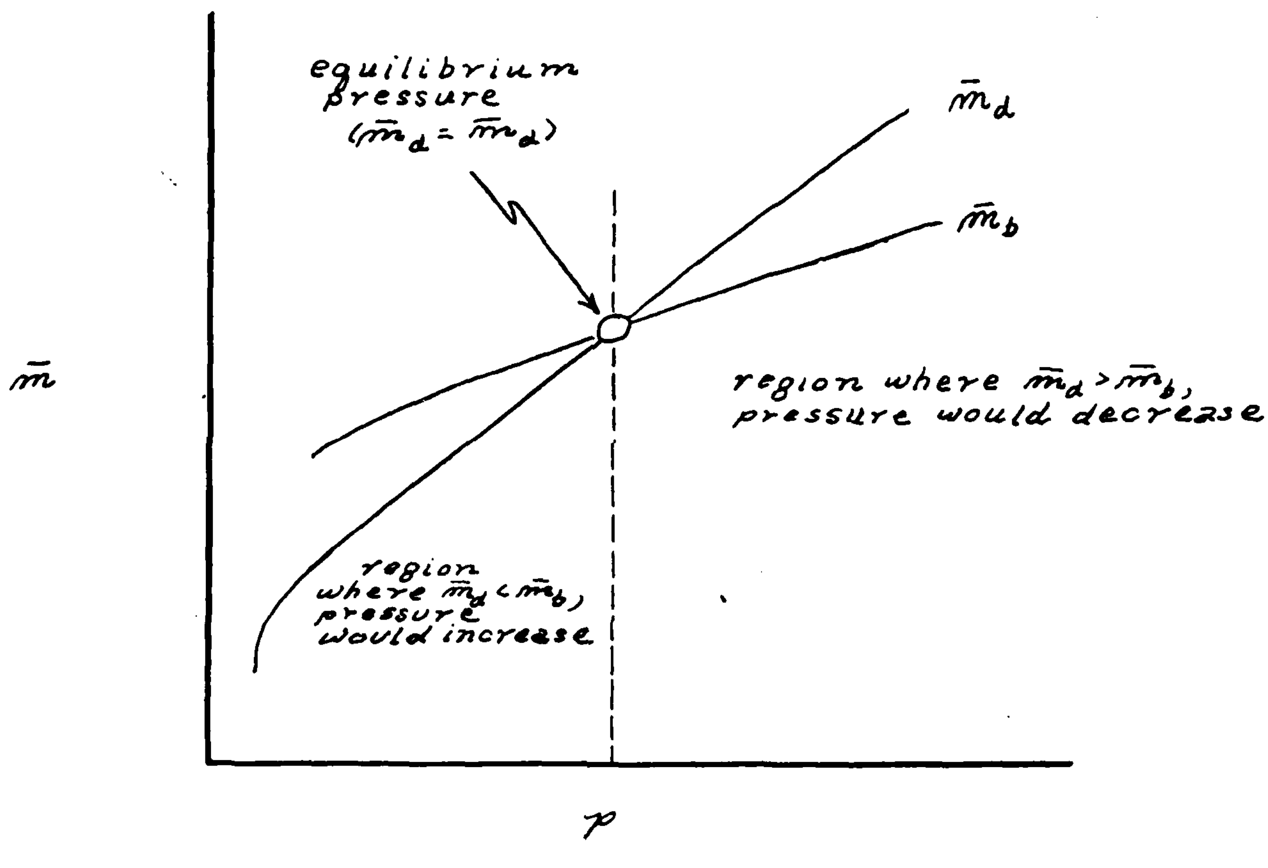

Fig. 1.3 Balance between mass burning rate and mass discharge rate to determine equilibrium pressure (pertains to a specific ratio of area of propellant burning surface to nozzle throat area, when p_{eq} is equilibrium pressure and other pressures represent off-equilibrium situations).

the difference between mass burning rate and mass discharge rate would tend to cause the pressure to change toward the equilibrium value (indeed, a propellant with steady state burning rate characteristics that did not show this property would be useless for most rocket applications). The details of how a combustor would recover from an off-equilibrium state depend on many non-steady features of the system, the most obvious of which is the accumulation of gas in the combustor necessary for pressure change. However, a complete representation of response to disturbances must consider how the combustion, flow, and mechanical system respond to transient disturbances. For example, a transient disturbance of the steady flow can induce disturbances in combustion, which can produce reinforcing pressure disturbances. The usual internal ballistic equations do not contain transient terms, and the response of combustion to transient flow is not generally known, so prediction of response to disturbances is not forthcoming. But in practice we find that disturbances do occur, and sometimes grow to intolerable levels. As a result, there is a special branch of the applied science of internal ballistics concerned with transient behavior of combustion-flow systems. As one might guess, this special "transient" branch of internal ballistics involves much tougher science, and is in a much less complete state of development than steady state ballistics. Further, it is much more difficult for a novice to understand. However, its general features can be understood by anyone with modest training in physical science and the determination to read on here.

When a local pressure disturbance occurs in the combustion chamber of the rocket motor, it propagates and is reflected repeatedly from walls and burning surfaces. In the process, the wave may strengthen due to interaction with combustion and mean flow in the cavity. Such repeatedly reflected waves tend to develop into discrete frequencies of oscillation characteristic of the cavity shape and size (Fig. 1.4). Under some conditions, such oscillations grow from minor disturbances present in any flow system. It often happens that some specific frequency of oscillation grows, a frequency corresponding to a specific mode of gas oscillation that is particularly suited to combustion "amplification".

The above behavior is illustrated schematically in Fig. 1.5a by pressure at a particular point in the motor, which is typical of thousands of motor test

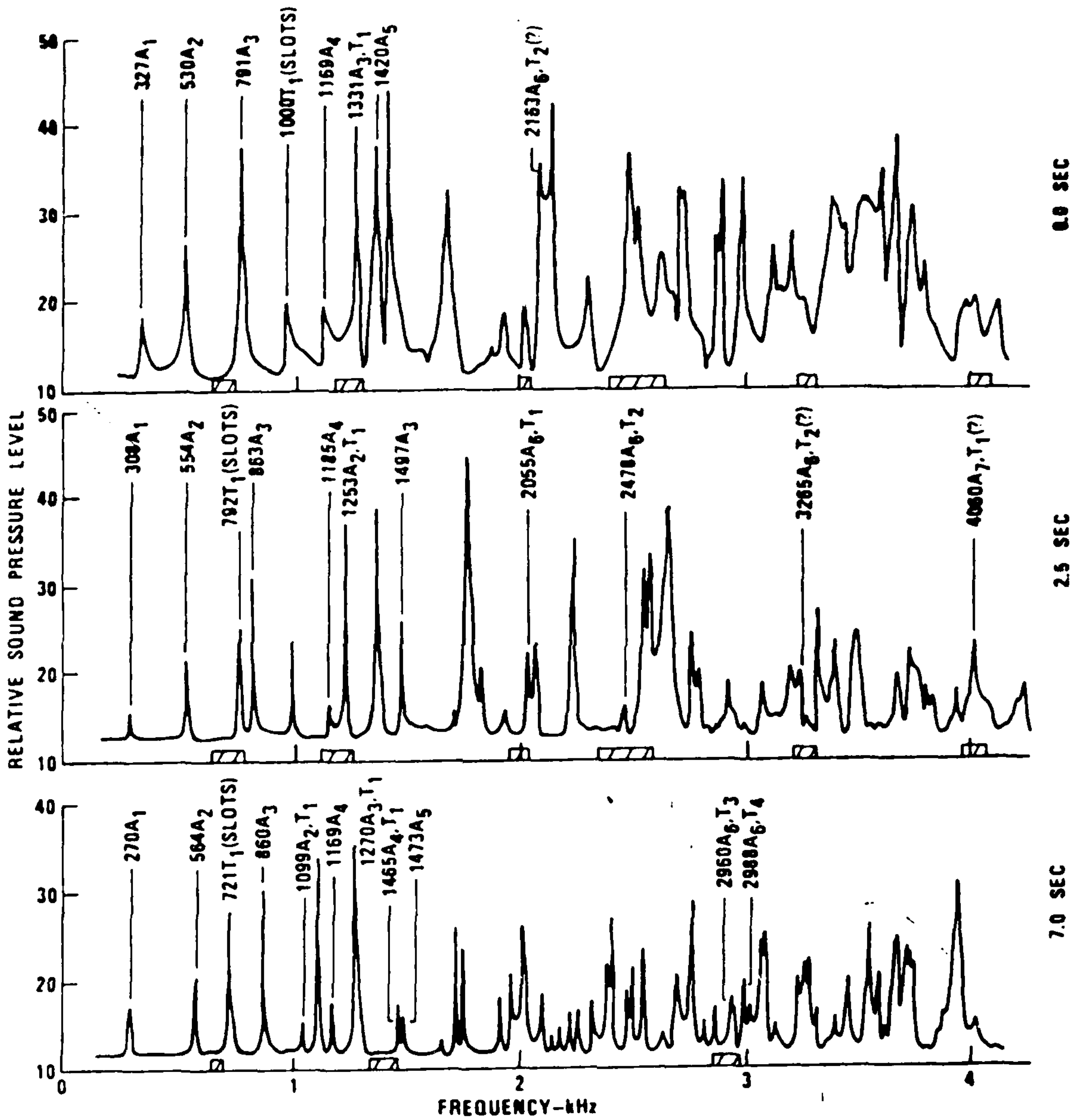

Fig. 1.4 Combustor cavity sound level response to a variable frequency sound input.

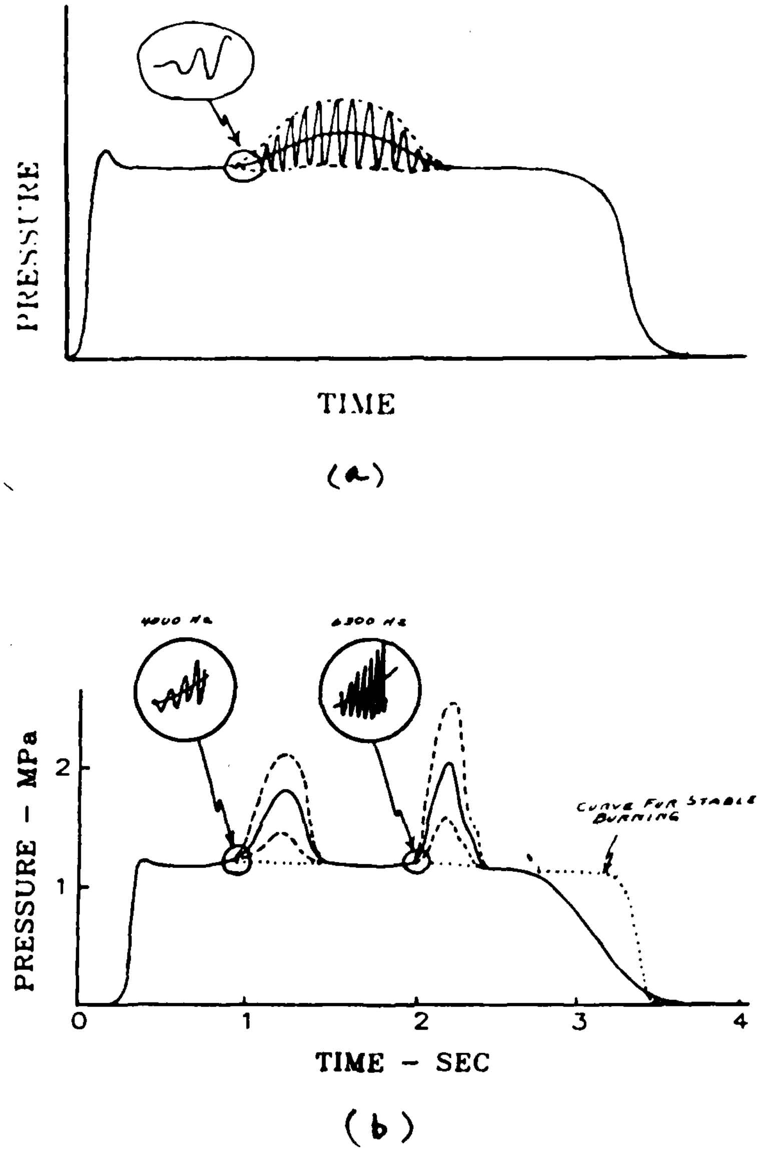

Fig. 1.5 Sketch illustrating spontaneous occurrence of oscillatory instability with associated increase in mean burning rate and pressure.

a) The solid curve is the actual pressure; the broken line is the pressure to be expected in the absence of oscillatory instability; and the dotted curve is the pressure indicated by low frequency response instrumentation.

b) Example of different modes of instability occurring at different (characteristic) times during a single test.

records. Oscillations develop at a characteristic time during burning, grow to peak-to-peak amplitudes that are often much more than 10% of the mean pressure, and then die off at some later point in burning of the propellant charge. Such behavior is often accompanied by large increases in mean pressure, and by severe vibrations in the motor case and other parts of the flight vehicle. In such systems we have come to realize that a sort of dynamic instability exists for the motor during part of its burning period. Under those particular conditions, steady state operation is simply not a normal mode of behavior.

Depending on the severity of oscillations, and the sensitivity of the flight vehicle to the oscillatory behavior, the motor may be unsuitable for use without modification of design or propellant. One of the most troublesome features of this instability behavior is its sensitivity to rather small changes in propellant, design, or operating conditions (pressure, temperature, etc.). This is illustrated by its appearance and disappearance in the way shown in Fig. 1.5b, where changes related to burning away of the propellant charge carry the system in and out of an unstable domain. This property means that some motors that seem to be free of the problem are later found to be unstable at extreme operating temperatures, or exhibit instability in production motors because of some small change in charge geometry or propellant characteristics part way through production. Such encounters with combustion instability can be extraordinarily costly to a weapons system program, causing rejected production, disrupted supplies of weapons, and loss of confidence in the weapon system (Ref. 1.8).

Fortunately, the risk of such costly encounters with combustion instability in service-qualified systems can be reduced by careful consideration of the problem during development. There is a tendency to shortchange these precautions because of unawareness of the risk or appropriate precautionary measures, and because of complacency after two or three motor programs in which no instability problems showed up. But the track record does not justify complacency, as instability has exacted severe penalties in many development programs. Even a careful use of current knowledge cannot absolutely assure avoidance of instability, but <u>timely</u> use of that knowledge can provide information about risk and reduction of risk early in a program when costs are low. The failure to use that knowledge can be very costly.

1.3 A Brief History of Combustion Instability in Solid Rocket Motors

To the non-specialist, a deeper insight into the full scope of the combustion instability problem can probably be gained from a historical review than from any other description of the problem. That context provides a framework in which the reader can identify with his own situation and see the interplay of many factors such as evolution of the scientific base; interplay of time and cost considerations with technical ones; interplay of propellant development, motor design and vehicle considerations; and the ever present problem of bringing the scientific base to bear on the problem at all relevant levels of system R and D.

The first encounters with combustion instability in solid rockets may have been in the pioneering work of Poole (Ref. 1.9) on internal burning cordite propellant charges in 1937. Performance of Poole's motors was reported to have been erratic, and there may have been a variety of causes. However, later experiences suggest that his combination of design and propellant would probably yield oscillatory combustion. There were no pressure measuring systems available then (or for the following ten years) that would show the presence of high frequency oscillations. Without such instrumentation, the excursions in mean burning rate (and corresponding excursions in mean pressure as in Fig. 1.5) that are caused by the oscillations are not distinguishable from those caused by a variety of other problems encountered in early developments, problems such as break up of propellant charges, plugged nozzles, and non-reproducible propellant properties.

Around 1940, some clues began to emerge in work in the United Kingdom and soon after at California Institute of Technology in the U.S.A. (Ref. 1.10-1.12) that pointed the way to recognition of oscillatory combustion even though the oscillations could not be measured. Dry-extruded double base propellant charges that were ejected during nozzle release (due to over-pressure) were found to be heated in a way not attributable to any conductive means, suggesting dissipation of vibration energy in the solid (Ref. 1.10). Twenty years later, this absorption of oscillatory energy was measured concurrently with measured oscillations (Ref. 1.13), and proposed as a significant factor in damping oscillations (Ref. 1.14).

Another feature of propellant charges recovered after erratic burning was evidence of localized enhanced burning rate, particularly in the perforations of internal-external burning charges (Fig. 1.6). The internal surface often showed rippled surfaces. Sometimes these charges were burst due to excessive pressure in the perforation (Ref. 1.4). These effects were believed to be due to some unidentified gas flow effect, and there was some evidence that burning returned to normal after fracture of the propellant tube. Charges were then tested in which holes were provided ahead of time to connect internal and external flow conduits (Fig. 1.7). It was found that the effectiveness of such web perforations depended on the pattern of the holes rather than their area, a result that led to speculation about the possible role of oscillatory flow. During the early '40s, many service rockets used internal-external burning solid double-base propellant charges stabilized by radial perforations, arranged in patterns determined by trial-and-error methods (Ref. 1.4). While the combined results suggested that oscillatory gas motion was involved in the erratic burning, no theory or measurements for oscillations were available until 1948.

While the studies with dry-extruded double base propellants were in progress at Cal Tech, oscillatory combustion was also suspected in testing by Hickman of solvent-extruded propellant charges using multiple tubular "grains" (Ref. 1.15). These "bundles" consisted of tubular grains that were small, and thin walled to provide large burning area and short burning time (suitable for certain Army applications). The grains were supported on an aft-end grid plate, and erratic behavior was initially blamed on break up of the charges due to differential pressure, and high acceleration forces in flight tests. It was suggested that these problems would be minimized if a metal cage structure were used in which each "grain" of the propellant charge was strung on a support rod. This resulted in elimination of irregular behavior. Word of this result led the dry-extruded propellant team at Cal Tech to use a longitudinal rod in the perforation of their larger single charges. Test results showed similar stabilizing effects. Since the rod reduced the area of the interior duct of the charge, it was concluded that pressure excess in the perforation was not the primary cause of irregular burning, but rather that oscillatory burning caused the excess pressure. On the other hand, stabilization by rods seemed to be contrary to the then prevalent speculation that the oscillations were analogous to "organ pipe" modes, as a continuous circular rod offered only limited means to interfere with longitudinal

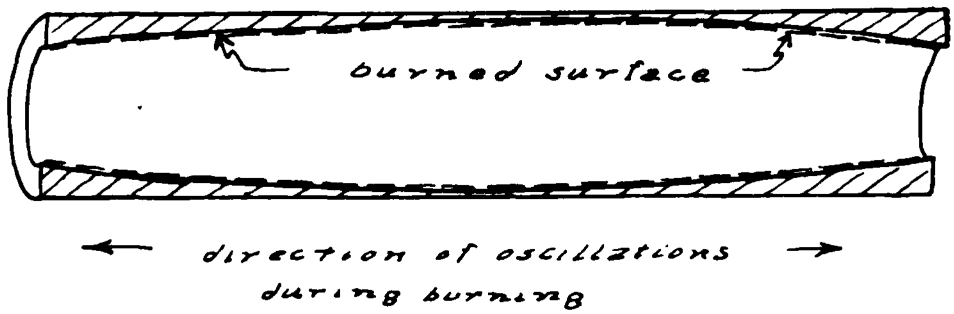

Fig. 1.6 Sketch of a cross section of a quenched internal-external burning propellant charge, showing evidence of local enhancement of burning rate (See Ref. (1.4, ____)).

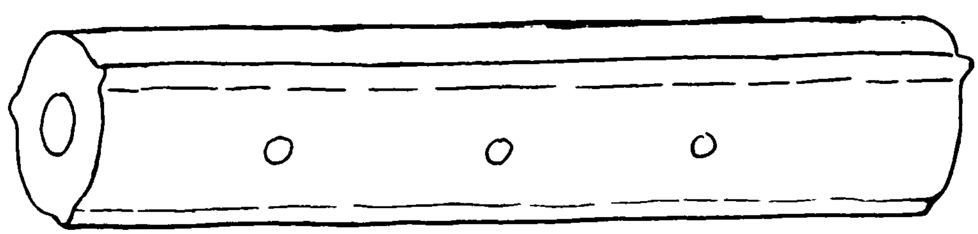

Fig. 1.7 Internal-external burning charge with radial holes to suppress instability in the inner conduit.

oscillations. This result led to the speculation that the oscillations were in transverse "modes", i.e., the pressure waves were reflected back and forth crossways in the perforation (for the designs then in use, the frequency of such oscillations would be 20,000 Hz, which explains why they could not be measured).

The above reasoning was largely intuitive, as the investigators were not trained in acoustic theory. However, it was reasoned that a modification of the shape of the internal conduit of the propellant charge might have a stabilizing effect analogous to the effect of the axial rod. This reasoning was tested first by cementing small longitudinal plastic ribs in the perforation, and then by extrusion of charges with propellant "ribs" (Ref. 1.4). Those methods were found to be completely successful in the charges tested, and provided the confidence needed for the important later transition to propellant charges with only internal burning surfaces (i.e., with external surfaces bonded to, or inhibited and close-fitted to the motor walls, Fig. 1.8). This transition in charge design (tried by Poole in 1937) was under active consideration in several laboratories in 1945-1946 (Allegany Ballistics Laboratory, Naval Weapons Center, and Jet Propulsion Laboratory (CIT). It should be noted that however suspicious investigators were of the involvement of oscillatory behavior in the experiences with irregular combustion, no measurements of such oscillations were available; the evidence was all indirect and the result of speculative interpretation. Only in the case of a very low frequency form of instability then referred to as "chuffing" was there direct measurement of pseudo-periodic behavior (Ref. 1.16).

As of 1946 it seemed significant that the irregular burning we now associate with oscillatory instability was observed only with double base propellants and charges with internal burning conduits. Tests on composite propellants (mainly hydrocarbon fuel with potassium perchlorate oxidizers) did not exhibit such behavior, and later work using ammonium-nitrate oxidizer also was free of oscillatory instability. This early result was sustained in later years, indicating that combustion of some propellants is "inherently stable". At the time, it was widely thought that the problem was uniquely characteristic of propellants based on nitrocellulose and nitroglycerin. The error of this judgement became evident when more energetic composite propellants based on ammonium perchlorate were introduced in the period 1947-1950 (e.g., Ref. 1.17). By this time most new designs involved internal burning propellant charges, which

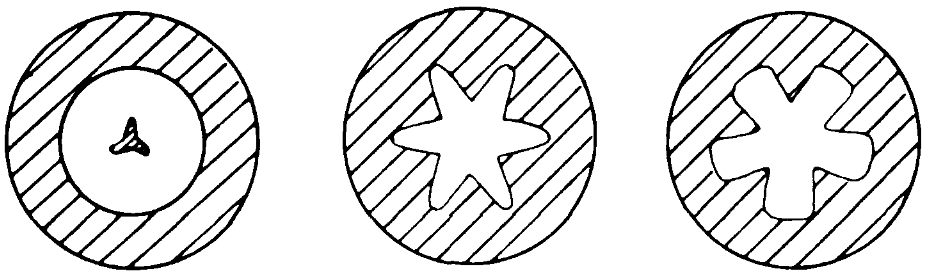

Fig. 1.8 Configurations of internal-burning charges that protect the motor case and have non-circular internal conduits that are relatively unsusceptible to transverse mode instabilities.

are much more susceptible to combustion instability than the external burning charges used in several World War II weapons (Fig. 1.9).

By 1948, it was established conclusively that the irregular burning problem was linked to oscillatory gas motions in the combustion cavity. Although still difficult, it became possible to measure the pressure oscillations and to relate them to natural modes of oscillation of the combustor cavity. The first direct measurements were reported by Hunt, Anderson and Swanson at the U. S. Naval Weapons Center (NWC) (Ref. 1.18). A classic paper by Smith and Sprenger of Aerojet Corporation (Ref. 1.17) showed the trend in oscillatory behavior in a study of an AP composite propellant in a family of charge configurations. The first paper presenting an analytical model of solid rocket combustion instability theory was written by Grad at New York University, apparently in collaboration with McDonald, who worked at both NWC and NYU (Ref. 1.19). These works were the first to establish the concept of spontaneous growth of oscillations in natural acoustic modes of the combustion chamber, and to point out the distinction between the well established dependence of steady state burning rate on pressure and the dynamic combustion response under non-steady (oscillatory) conditions. This latter (dynamic response) concept was examined by several investigators in the 1950s (Ref. 1.20-1.22), but was not formalized in a realistic way until ten years later in 1959 with the classic work of Hart and McClure (Ref. 1.23).

During the period 1948-1958, combustion instability was a common problem in motor development programs. The encounters were substantially summarized by Price in 1961 (Ref. 1.24). No strategy of avoidance of the problem was evolved, partly because motor developers did not understand the problem, and partly because correction was not prohibitively expensive with the moderate size motors of the time. When instability was encountered, it was controlled by trial-and-error modifications of charge geometry, or introduction of "resonance" rods (Ref. 1.25) analogous to those discovered in the mid-'40s. Remedy was aided by measurement of the oscillation frequency, identification of the unstable mode of oscillation, and adoption of geometries that blocked the oscillatory motions of that mode (Fig. 1.10). This was not always simple because the remedial measures, often referred to as "black magic", were inexact, because the oscillation measurements were often lacking or poor, and because modified designs had to be qualified over a wide range of operational temperatures. Some motors

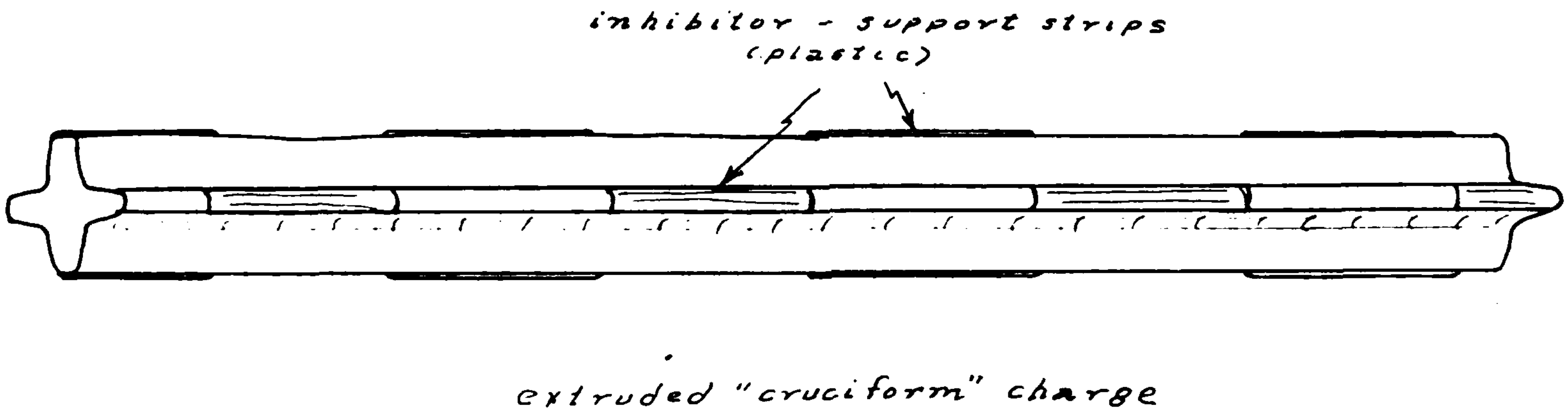

Fig. 1.9 External-burning charge typical of the 1943-1948 designs that were less prone to combustion instability.

(Figure in preparation)

Fig. 1.10 Mode shapes and blocking geometries.

went into service with designs that consistently gave moderate oscillations that were either not recognized, or deemed to be tolerable. In some cases, this "residual" oscillatory behavior proved later to be quite intolerable due to unexpected interaction with guidance, control and fuse function in the all-up service systems. Such revelations later in the system development or after start of production can be very costly because of the necessity to go back and requalify a modified propulsion system, and because of the high cost of development and production delays. In some cases, service limits were accepted (e.g., narrower operational temperature limits) in preference to accepting the costs of modification and requalification of the motor.

Obviously, the "easy out" from all these problems with oscillatory combustion would be to use a "stable" propellant, such as the potassium perchlorate or ammonium nitrate formulations. Unfortunately, these propellants had several undesirable characteristics, the most important of which was low specific impulse. No higher energy propellants have exhibited the consistent stability of these propellants. As understanding of the phenomenon has increased, it has become evident that susceptibility to instability is closely related to several of the more desirable propellant characteristics such as high energy, high burning rate, and low concentration of condensed reaction products ("lo-smoke" characteristics). Thus, nature offers no easy out for the instability problem, but instead demands continuing vigilance and compromise. This is nothing new in the high energy propellant and rocket motor business, which is constantly concerned with courting disaster in the quest for higher performance. However, propellant formulators are more directly motivated to recognize more direct hazards (e.g., susceptibility to unwanted ignition, detonation, or mechanical failure) than the vaguely understood possibility that their newest propellant might exhibit oscillatory combustion in a motor. In the 1950s there were no handy tests to rate the susceptibility of a propellant to oscillatory combustion (and even today it is a costly and inexact business).

In the late 1950s, powdered aluminum was introduced as a fuel ingredient in composite propellants. This modification offered more dense propellants and higher specific impulse. It also resulted in complete elimination of oscillatory combustion in the motors of that period. Aluminum looked like the "easy out", particularly at that time when the penalty of a smoky exhaust plume was deemed

acceptable in exchange for higher performance. However, this was also the time when serious commitments were being made to development of much larger motors with the high energy propellants, and there was an uneasy feeling that the reprieve from instability problems brought about by introduction of aluminum powder might not apply to large motors.

In the U.S.A., a Defense Department Committee was set up to examine the risk of combustion instability in future programs, which was deemed to be particularly important for large motors because the cost of testing was so great that trial-and-error methods of correction would be very costly. After thorough review, the committee (Sage, Ball and Avery, Ref. 1.26) warned that there was no basis for confidence that aluminized propellants would be stable in large motors, and that a better fundamental understanding should be sought to avoid costly problems in large-motor development programs. Even before that report was made, considerably expanded research was begun at the Naval Weapons Center under sponsorship of the Polaris program, and at other laboratories under U. S. AFOSR, ONR and Army support. As a result of the DoD study, the Advanced Research Projects Agency of the U. S. DoD established a further series of studies, including an assignment to F. T. McClure at Johns Hopkins University Applied Physics Lab to organize a technical panel for coordination of research and exchange of information. This was the beginning of an intensive effort to enhance information exchange and evaluation, which continues to the present as the Combustion Working Group of the Joint Army-Navy-NASA-Air Force Interagency Propulsion Committee.

During the 1956-1966 period, the magic of aluminum as a suppressant became better understood, as did its limitations. It was shown that the fine oxide smoke resulting from aluminum combustion acted very effectively to damp high frequency gas oscillations. Even a few percent of aluminum was often sufficient to yield stable combustion. However, the damping effect was small at the low oscillation frequencies of large rocket motors, and oscillatory behavior was encountered in several motor programs at frequencies in the 200-2000 Hz range (thus validating the concern expressed by the 1959 DoD committee report (Ref. 1.26). In addition, concern developed over three new trends in motor development. One was the thrust toward evaluation and use of technology for very large motors that would have natural combustor mode frequencies down to 10 Hz.

Another was a return to low smoke propellants in many tactical applications as a means to frustrate countermeasures. The third trend was toward complicated charge and motor geometries, especially in upper stage and space motors. The risk of combustor instability in the large motors (such as the Titan IIIC and Space Transportation System ("Shuttle") boosters) was unknown, and the return to low smoke propellants in tactical missiles was guaranteed to bring instability troubles. The motors with complex interior geometries gave rise to complicated internal gas flow fields and interactions with combustion. These new developments, along with the problems with existing motors, led to increased pressure for procedures for prediction of motor stability as part of the design-proposal activity. We will return to this point shortly, but divert now to a related development case history that serves well to illustrate more clearly some of the vague generalizations in the foregoing regarding the compromise of missile systems by combustion instability.

In 1959, the U. S. Navy started development of a motor for a torpedo tube launched surface-to-surface weapon called Sub Roc. The motor used an ammonium perchlorate-polyurethane-aluminum propellant. No serious consideration was given to the possibility of combustion instability, primarily because aluminum had become accepted as an "easy out" cure for instability. The motor involved considerable new hardware technology, which was evaluated first in static firing tests in 1/4 length motors for economy reasons. No problems were encountered with instability in these tests or later 1/2 length motor tests, or in several full length motor tests. Then an abrupt transition from steady burning to severe oscillations at 180 Hz occurred during one firing (Ref. 1.27). The oscillatory behavior (first axial mode) was accompanied by a 30% increase in mean pressure. After several stable firings, the instability was repeated. No special conditions could be linked to the unstable motors, except that oscillations started with a strong initial pulse. Such behavior had been observed in earlier research studies where nominally stable motors were found to develop growing oscillations when pulsed by firing of a powder charge into the motor (Ref. 1.28, 1.29). The sporadic nature of occurrences of instability in the Sub Roc program posed a serious problem, because it indicated that identification of a statistically reliable "fix" for the motor would require a large number of costly full scale motor tests. A panel of experts proposed a set of 19 possible fixes. It was recognized that some cause for spurious initiation of oscillations was

present, and that the problem could possibly be solved by elimination of that cause. However, it was also considered to be desirable for the motor to be stable even when a pulse occurred. Ejection of parts of the spent igniter case was considered as a possible source of pulsing, and the igniter was modified to assure retention in the motor. Based on research studies of similar behavior at NWC (Ref. 1.28, 1.30), it was also proposed that a finer aluminum powder be used in the propellant. After these two changes were made, no further encounter with oscillatory behavior occurred. Comparison of the original and the modified propellants in the NWC laboratory burner showed the modified propellant to be more stable in the NWC burner (Fig. 1.11), even when the burner was pulsed (Ref. 1.30). It was not determined whether the change in aluminum particle size improved stability by increased damping (more favorable aluminum oxide droplet size) or by a less destabilizing response of combustion to flow disturbances. Whatever the mechanisms, this motor program dispelled the myth that aluminized propellants were inherently stable. It also introduced the development community to: a nonlinear (pulse initiated) form of instability that was under investigation by the research community; the nightmare statistics of a phenomenon that gave no symptoms in repeated tests and then appeared in catastrophic form; the need to avoid designs that allowed ejection of solid debris from the motor; and the complexity of scaling laws for combustion instability. These aspects of the instability problem were to be encountered in later programs, and became major aspects of research programs. It is worthy of note that the complex nonlinear interactions of the side-burning propellant charge with large amplitude axially oscillating flow in the combustor (as in the Sub Roc system) is a very complicated phenomenon that has only recently (in the 1980s) begun to receive rigorous modeling efforts. This case history illustrates another important lesson about dealing with the problems of combustion instability, one that is all-too-little recognized. The changes in the Sub Roc propellant and igniter design that so quickly resolved the problem were proposed as a result of research sponsored at an entirely different laboratory by an entirely different development program (Polaris). This research was part of the expanded research motivated by the risk so well stated by the DoD Committee in 1959. The communication that led to timely transfer of the critical information to the Sub Roc program was due to the enhanced efforts at communication of current results. If this atmosphere of timely and vigorous collaboration had not existed, the Sub Roc program would have

(Figure in preparation)

Fig. 1.11 Comparison of pulsed instability of original and "stabilized" SubRoc propellants in research burner.

experienced major delays. In the last 20 years, this kind of collaboration among research and development teams regarding combustion instability has become commonplace, although poorly documented and sometimes absent. Since the administrative context provides few clear-cut incentives for such collaborative efforts (such as funding for special tests or travel expenses), its success is a testimonial to the dedication of the working level participants and the desire to bring current research to bear on practical problems. A development program in trouble rarely has, or will allocate, funds to meet the extra costs of outside participants. Further, the contributions of the outside participants are rarely acknowledged in any formal way.

Returning to the progress and problems in the early 1960s, some of the notable advances were:

a. Some significant progress in basic understanding of propellant combustion was made, which was essential to realistic analytical modeling of dynamic combustion response. These advances included clarification of the self-deflagration process of ammonium perchlorate, combustion of aluminum, and surface features of burning composite propellants. Methods of combustion photography, interrupted burning, and microscopic analysis of quenched samples played important roles in these advances.
b. Laboratory scale tests were developed for determination of the relative susceptibility of propellants to oscillatory combustion. The "T" burner, developed originally at NWC in the late 1950s (Ref. 1.31-1.33), evolved into several forms, and was used in around 20,000 tests in the 1960s to show the trends of combustion response with frequency, mean pressure, and propellant variables.
c. Several analytical models of the dynamic response of combustion to incident pressure disturbances were developed, which provided a much better understanding of how propellant combustion responds to flow disturbances (Ref. 1.34).
d. More realistic analyses were made of the acoustic modes that occur in combustors, including the description of the effect of the mean flow field, nozzle, and coupled vibration of the propellant charge and motor case (Ref. 1.35-1.38).

e. Advances were made in overall stability analyses (e.g., Ref. 1.39, 1.40) and physical insight.

Progress in the 1960s and 1970s was intensively reported in the literature, particularly in the annual proceedings of the meetings of the U. S. Joint Army-Navy-NASA-Air Force Combustion Working Group, published by the Chemical Propulsion Information Agency. In addition to continuing improvement of basic experimental and analytical methods, attention was focused particularly on the emerging problems noted above (e.g., stability characteristics of new low-smoke propellants, stability of aluminized propellants in large motors, and stability of motors with complex geometrical features). A problem in a major operational system in 1969 led to intensified efforts to conduct analytical-computational evaluations of motor stability prior to final design and testing. Intensified research efforts also were stimulated by this operational system problem, illustrating the positive side of an unfortunate tendency for national efforts to peak and decline according to the severity of current operational problems with combustion instability. The system problem referred to above provides so much insight into the realities of "managing" the combustion instability problem that it is described in more detail in the following.

The case history of the Sub Roc system described previously illustrated the problem of nonlinear axial mode instability, in which a margin of stability exists that leads to stable tests until finite disturbances trigger severe instability. In that case history the problem was resolved by propellant changes <u>during the development program</u>. A rather different scenario was presented <u>during production</u> of the Minute Man Wing II Stage III motor (Ref. 1.41), with consequences so serious that the U. S. Air Force and its Rocket Propulsion Laboratory initiated a substantially enlarged program of combustion instability research to forestall recurrence of such program problems (Ref. 1.42).

The Stage III motor went into production with a recognized oscillatory instability that gave pressure oscillations with peak-to-peak amplitude of approximately 10% of mean pressure, with primary frequency of around 450 Hz. Production specifications set a limit on amplitude, and no problem was encountered with staying within this specification in quality control testing (the instability was surprisingly reproducible, and functioning of the missile system was not initially impaired). However, about halfway through the production program an undetected change in oscillatory behavior occurred, that

later led to several flight failures. A review of test records showed that the predominant oscillatory frequency had changed from 450 Hz to 1250 Hz. The review traced the failure to a resonant vibration-induced failure of the thrust direction control system. Review of the production records linked the change in oscillatory behavior to a change in the supply source of the aluminum powder in the propellant. The powder met the usual specifications, but combustion studies on the propellant showed a substantial difference in combustion behavior of the "new" aluminum. While the exact mechanism responsible for the change in frequency of the oscillatory behavior was not determined, the most likely cause was a change in damping behavior of the aluminum oxide products of combustion. The modified combustion led to a change in the size distribution of the product oxide droplets that was conducive to better damping at 450 Hz and less damping at the third axial mode frequency of 1250 Hz. At the time, methods for measuring the change in dynamic response of the combustion were only marginally adequate, so that the importance of this as a contributing effect in the change in instability was not evaluated.

After the link with aluminum sources was established, motors using the modified aluminum were recalled from service and a modification of the control system was made to prevent the vibration-induced failure.

This case history serves to illustrate several aspects of the combustion instability problem that deserve emphasis:

1. The total cost was very large because it emerged after the missile system was deployed.
2. The problem arose because of a change in a propellant ingredient supply that was not (and still is not) covered by quality specifications. *

* The change in the aluminum resulted from a switch by the supplier of the powdered aluminum fuel ingredient to delivery from a different production plane, because of a fire in the original plant. The "new" aluminum powder had a different oxide coating that changed combustion. Quality of oxide coating on the aluminum particle is not covered in quality acceptance specifications, although it has been shown to be important in subsequent combustion research studies.

3. The motor was qualified for production with recognized combustor instability, and the failures resulted from changes in stability that were not covered by quality acceptance criteria or recognized in routine acceptance firings.
4. The motor failures were due to a mechanical resonance with combustor frequency, indicating the importance of "hardening the bird" to combustor frequencies if combustor stability is not assured.
5. The technical capability to diagnose the cause of the flight failures and trace it back to the point of identifying the production motors that needed modification was made possible by the expanded research following the recommendations of the 1959 DoD Ad Hoc Committee. The enhanced support of the NASA starting in 1963 was also an important factor.
6. The episode led the U. S. Air Force to establish a substantial in-house capability in the area of combustor instability, and related contracted research programs, based at the Air Force Rocket Propulsion Laboratory.

1.4 Practical Nature of the Combustion Instability Problem

From the case histories cited above, it is evident that it is not only difficult to consistently avoid combustion instability, but also to predict its effect on a flight system. From the practical viewpoint, the problem must be addressed at all levels of system planning, management and development. Somewhere along the way in every motor development program, the decision is made (overtly or by constraints due to other decisions) whether oscillating behavior will, or will not, be tolerated. If it is not to be tolerated, then there should be some assessment of risk made in choice of propellants, charge design and motor design; and test motors should be so instrumented that oscillatory behavior will be detected. Even if no evidence of oscillatory behavior is observed, the issue should be reassessed before commitment to final design, and production specifications should reflect safeguards against emergence of the problem due to subsequent propellant and design variations made by production engineers who are not familiar with the risk. These issues will be discussed in more detail in Chapter 3 (see also Ref. 1.43), but it is important to stress here that the longer the delay in consideration of combustion instability during a development program, the more costly and difficult will be the remedy should the problem

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arise. This is so because of the progression of commitments to propellant and design that get made, the increasing cost of getting diagnostic measurements, and the high cost of going back to change propellants and design that have in other respects been accepted as "qualified".

It is usually delay in consideration of combustion instability that leads to decisions to "live with it" when it is found in a propulsion system. When commitments of propellant, design, cost and time schedule are far advanced, it may seem wiser to "harden the bird" to vibrations and other instability induced effects. Given the unfortunate circumstances, this decision may be the best one to make at that time, but the risk needs to be fully understood. In complex flight systems it is not easy to anticipate all the ways that effects like combustion-induced vibrations can interfere with operation, and it may be very costly to qualify the system for safe operation in the adverse environment. Further, monitoring and controlling the adverse environment becomes a continuing production control problem that usually reverts to management by production personnel who have minimal knowledge of the problem. On the other hand, there are instances (usually involving simple flight systems) where motors having significant oscillatory behavior have gone into production and service without any adverse effects. The decision to live with unstable combustion, as illustrated by the Minuteman system described earlier, is a very serious decision (as is the situation that forces that decision). From the viewpoint of the system manager, it is important to bring "instability specialists" into the planning early, on the principle that an ounce of prevention is worth more than "a pound of cure". The same "clinical" attitude applies to early detection, which can greatly simplify the cure. If the goals of the present report are achieved, the level of understanding all along the sequence of planning, development and production will be enhanced, the population of specialists will be enlarged, and exploitation of available knowledge will be made easier. For this report, that is the "practical" goal. There is also a more fundamental goal of aiding the specialist to come to grips with a vast and diverse body of knowledge that is otherwise poorly documented in primitive and fragmented form in original articles in archival journals and obscure reports.

Ultimately, one may hope that enough will be known about the complex coupled flow and combustion processes to permit advance design for stable operation. If that goal is achieved and sustained, it will be a result of future scientific advances, full utilization of existing knowledge, and timely availability and utilization of qualified specialists in the subject.

Chapter 2

COMBUSTION CHAMBER PROCESSES

2.1 Introduction

In this section, the elementary concepts mentioned in Section 1.2 are described more fully and concisely so that the reader can be prepared for more technical and rigorous later description if needed. Should the later descriptions be overly complex for the needs of some readers, this chapter will provide the necessary background for a qualitative understanding of the physical and combustion processes and the technical language needed for persons who have to deal with instability as peripheral to their main concerns.

Before becoming immersed in a discussion of the details of combustor processes, it is appropriate to recall the primary objective of the rocket motor. It is a device designed for high capacity conversion of stored chemical energy into thermal energy and then into directed mechanical energy. The conversion from chemical to thermal energy is accomplished by high pressure combustion of the propellant, while the mechanical energy is acquired by acceleration of the high pressure gases down the pressure gradient in the combustion chamber and nozzle channel. The combustion and flow systems are mutually interactive and it is this interaction that gives rise to the possibility of oscillatory behavior. It is these contributing processes and their interaction that will be described in the following.

2.2 Nature and Diversity of Combustion

A solid propellant is a body of chemically reactive ingredients, which is prepared by any of several processes. Its composition and physical structure are required to be uniform on a macroscopic scale. Many are highly heterogeneous on a microscopic scale (< 1 mm) (Fig. 2.1). Propellants are generally very poor heat conductors. Therefore, they can be heated rapidly to a surface temperature that leads to chemical reaction and flame at the surface,

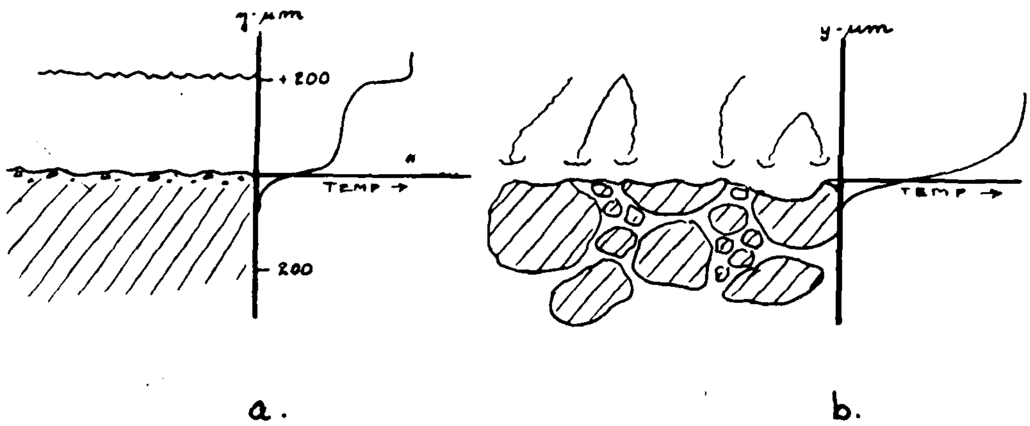

Fig. 2.1 Illustration of the propellant combustion zone and comparison of heterogeneous and homogeneous propellants:
a) homogeneous propellant, e.g., NC, NG, and
b) composite propellant, e.g., PBAN-AP.

while remaining cool a few mm below the surface. Heating the surface rapidly to start burning is called "ignition" and is done by auxiliary devices in the rocket motor called igniters. During the ignition phase of a motor, the flame is spread over the charge surface and the pressure increases under the combined influence of the igniter and the ignited propellant. Some surfaces of the propellant charge are protected from heating by bonding to a non-burning "inhibitor" or to the motor case (Fig. 2.2). If all goes well, when the igniter is fired the pressure in the combustor rises to the desired value at a time when the exposed surface is fully enflamed and the igniter is just ending its output.

At this point, the burning surface is moving inward into the solid at a velocity of order 10^{-2} m/sec. The vapors from the solid surface are around 600^{o} C, and move away from the surface at roughly 1-10 m/sec. These vapors represent decomposition products of the propellant ingredients. Decomposition is usually (but not always) endothermal, with the heat for decomposition coming from energetic reactions in the vapor phase above the surface. Most of the energy release occurs in the vapor outflow within 1 mm of the solid surface. The details depend on the nature of the propellant and the environmental conditions (pressure, propellant initial temperature, influence of combustor flow conditions near the burning surface). Exothermic reactions may occur at more than one location in the overall combustion layer, with those nearest the burning surface tending to influence burning surface regression rate most effectively because heat transfer to the surface is greater. Exothermic reactions sometimes occur <u>in</u> the burning surface and are particularly effective in determining the burning rate. Certain propellants are practically homogeneous (e.g., nitroglycerin-nitrocellulose propellants) and the combustion zone can be thought of as a sequence of reaction layers that may be viewed as successive planar flames (Fig. 2.1a). Other propellants are sufficiently heterogeneous so that the flame structure is affected by the need for lateral diffusion of vapor reactants so they can react with each other. Since diffusion occurs more rapidly when the scale of heterogeneity is small, the heat release is then closer to the surface and burning rate is higher. In analytical models, the geometrically complex nature of such combustion zones is

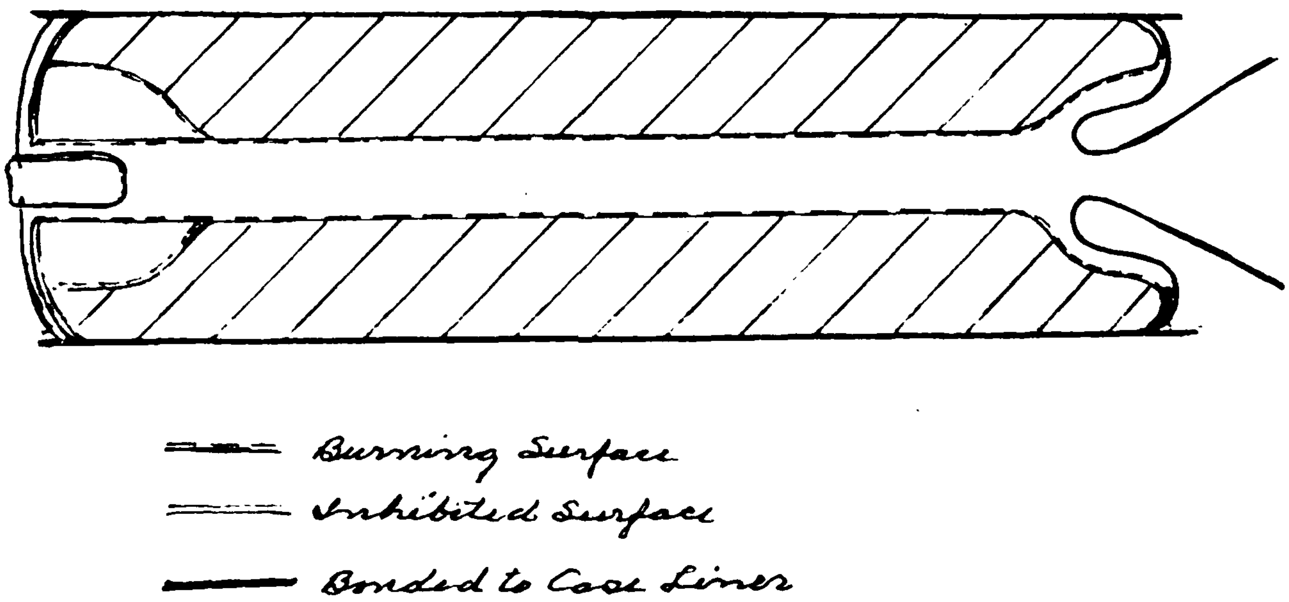

Fig. 2.2 Illustration of the arrangement of the igniter and of exposed, inhibited, and bonded propellant surfaces.

generally modeled in a manner similar to the homogeneous propellants (i.e., a sequence of planar flames). Then the position of each kind of flame is calculated as some kind of an average stand-off distance dependent on scale of heterogeneity (Fig. 2.1b).

We are concerned here with both steady and non-steady burning. For homogeneous propellants, "steady burning" means that the temperature profile in the combustion zone (and related composition profiles) remains invariant with time, and moves with the propellant surface as a wave of constant velocity into the propellant (the burning rate of the propellant). Although theory is good for understanding why some propellants have different burning rates than others, accurate data on burning rate is obtained from direct measurements on burning samples. Fig. 2.3 shows typical steady state burning rates for some homogeneous propellants, and shows how they depend on pressure and temperature.

The steady state burning rate of an inhomogeneous propellant is defined only in terms of the rate of regression of an average surface, since the regression rate may vary from place to place at any given moment (due to inhomogeneities). Fig. 2.4 shows a high magnification picture of a quenched surface of a composite propellant, from which it is evident that surface behavior is dependent on local composition and the associated flame complexes above the burning surface. While such propellants burn unevenly on the microscopic scale, the high burning rate sites are generally short-lived due to the disorder in the propellant microstructure. The surface remains flat on a macroscopic scale and the regression rate can be characterized in the same way as a homogeneous propellant when viewed on a distance scale larger than a few millimeters.

As one might suspect, propellants with low burning rate have relatively thick combustion zones and thermal waves in the solid, while high burning rate propellants have thin combustion zones and steep temperature gradients. High rates result from high pressure and/or temperature environments, fine particle sizes, high energy ingredients (high flame temperature), and use of catalysts that enhance near-surface exothermic reactions or move outer reactions closer to the surface. Some typical combustion zone dimensions are shown in Fig. 2.1. As a matter of perspective, it is helpful to note that the thickness of the

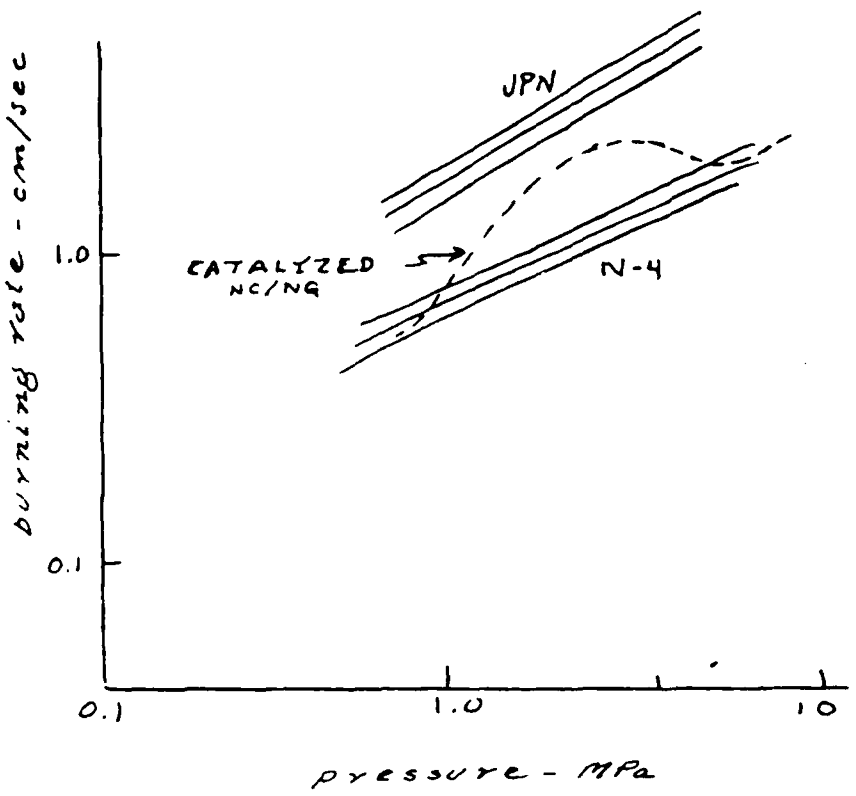

Fig. 2.3 Steady state burning rates of homogeneous propellants.

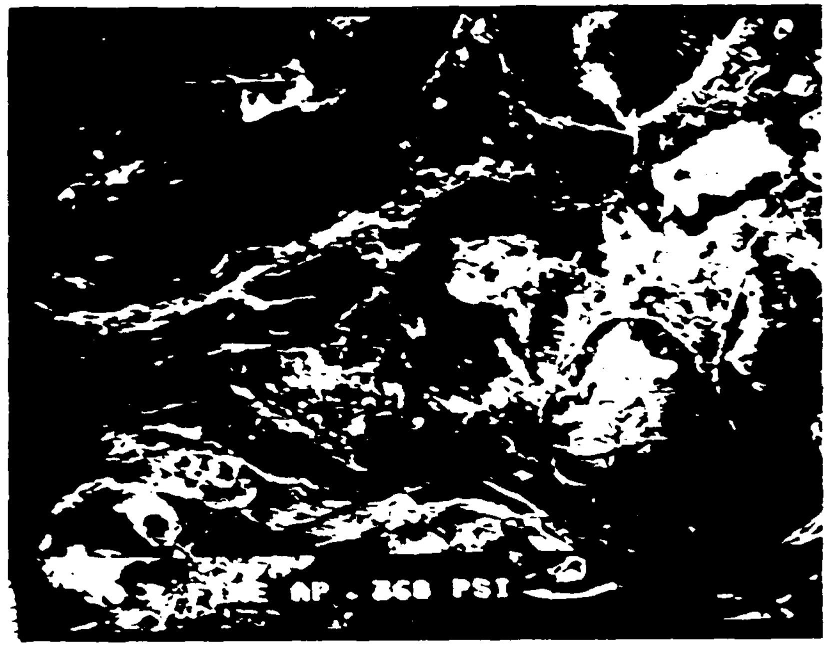

Fig. 2.4 Burned surface of an AP-PBAN propellant quenched from ___ MPa burning by rapid depressurization.

steep part of the thermal wave in the solid is typically less than the diameter of oxidizer particles, and that an oxidizer particle is traversed by the burning surface in roughly 10^{-2} seconds (100 μm at 1 cm/sec).

2.3 Combustor Gas Flow Field

Under normal (steady) operation of an SRM, a reasonably steady pressure is reached after ignition. In a simple interior geometry, gases leaving the lateral burning surfaces of the propellant turn and flow toward the nozzle (Fig. 2.5a). While this gas flow field changes during burn-away of the propellant at the cavity walls, this change is slow compared to flow times in the combustor, so that calculations of flow usually are based on steady flow theory. Because of the increasing mass flow toward the nozzle end of the combustor, the velocity increases with distance downstream from the forward end and there is a corresponding drop off in pressure. The operating pressure is determined by a balance between mass burning rate and mass discharge rate through the nozzle, $\dot{m}_b = \dot{m}_d$. Calculation of equilibrium pressure thus requires determination of $\dot{m}_b$ by integration over the charge surface

$$\dot{m}_b = \int_0^L \rho_p r \, dS_c = \int_0^L \rho_p r \, q \, dx \qquad (2.1)$$

where r is the burning rate of the propellant and S_c is the area of propellant charge burning area upstream of x. The rate, r, will vary with location (x) because the burning rate depends on pressure and other properties of the flow field. q is the perimeter of the burning surface at the station x, and ρ_p is the density of the solid propellant. For internal ballistic calculations, the flow field is usually calculated using a "one-dimensional" representation of the gas flow, implicit in the above equation (one-dimensional steady flow with mass addition (Ref. 2.1, 2.2). However, a more rigorous analysis may be

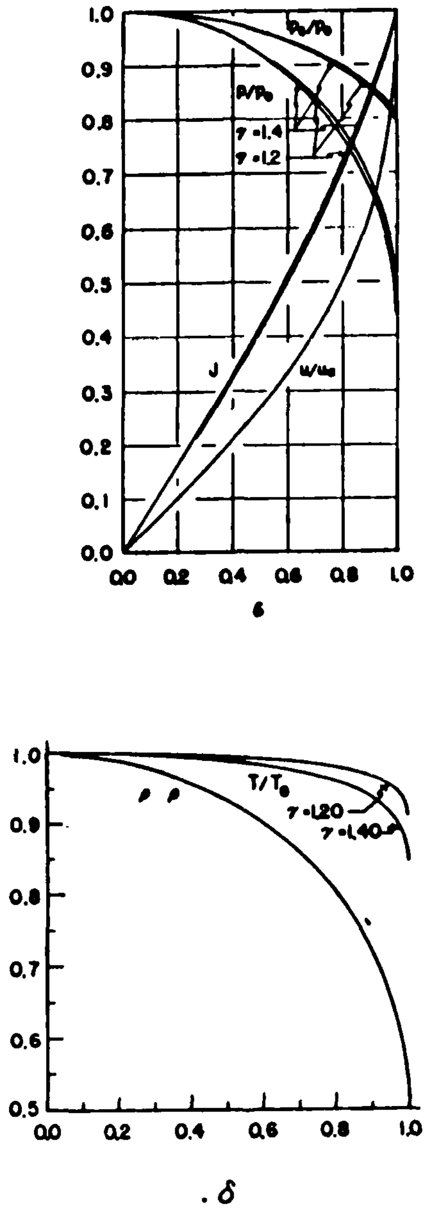

Fig. 2.5 Solution of the steady 1-D mass addition flow problem for geometries of uniform conduit cross-sectional area (from Ref. 2.1).

required for motors with very complicated interior geometry. Although rather approximate, the simple flow analyses seem to describe the features most important for predicting steady state motor performance. An example of the dependence of flow variables on axial location is shown in Fig. 2.5b.

2.4 Oscillations

The most conspicuous aspect of combustor instability is the presence of periodic oscillations in pressure, which are accompanied by less easily measured oscillations in other variables of state of the gas (temperature, density, etc). In the simplest cases, these oscillations are the same (or nearly so) over the entire combustor volume, a behavior that is possible only at low frequencies of oscillation and ordinarily experienced only in low L^* motors. At higher frequencies, the oscillations involve surging motions of the gas, with pressures in one part of the combustor peaking when the surging gas has come to rest at that location, and peaking later "at the other side of the cavity" when the surging motion has come to rest there. One can picture the moving gas as having momentum that produces a compression of the gas when the motion approaches a cavity wall. The resulting compression stops the motion and then sets the gas in motion in the opposite direction. This sets the stage for a compression on the opposite wall of the cavity. This is most easily visualized by the gas motions in a straight pipe with closed ends (Fig. 2.6). The surging motion is in the longitudinal direction of the pipe, and the frequency of oscillation is given by

$$f = na/2L$$

where L is the length of the pipe, a is the velocity of sound in the gas, and 2L/a is the time for a pressure disturbance to travel the length of the tube and back. The factor n is an integer and indicates the possibility that gas may be set in motion in different directions in different parts of the cavity at the same time. This is illustrated in Fig. 2.6b, which shows the motions for n = 2. The timing of the oscillation in the two halves of the cavity is

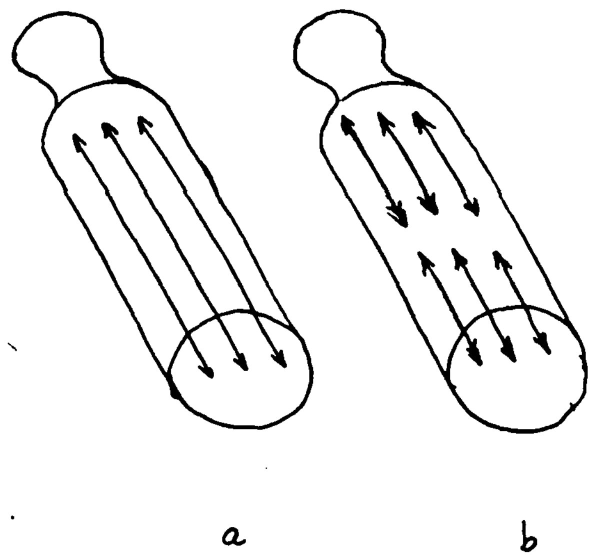

Fig. 2.6 Gas motion during longitudinal oscillations in a simple cavity geometry.
a) first standing mode, and
b) second standing mode.

such that the surging gases in the opposite halves of the column approach the midpoint of the cavity at the same time and "bounce off each other" much as if there were a wall there. Thus, in this "second mode", the pressure disturbance in each half makes a round trip of a half length of the column in a time $2(L/2)/a$, with a frequency a/L. In the language of acoustics, this is the "second longitudinal mode" of the cavity and n is the mode number. It is not difficult to visualize that other modes with $n > 2$ can occur, or that similar oscillatory motions can occur in the crossways direction in the tube (transverse modes).

In practice, oscillations can occur in more than one mode at a time and change during burning of the propellant charge as the geometry of the cavity changes. This is illustrated in Fig. 2.7, which is a "modal" analysis of the oscillations in an actual motor, showing the amplitude and frequency vs time of various modes. The lowest frequency is the first longitudinal mode and the frequency remains constant because L doesn't change during burning. The high frequency corresponds to a transverse oscillation and the frequency decreases as burning progresses because the transverse cavity dimensions increase as burning progresses. The display of oscillation frequency and amplitude vs time for an oscillating motor is often called a "waterfall diagram".

The surging motions described above correspond to a special class of oscillatory behavior referred to as "standing acoustic modes". These relatively simple modes are the ones most commonly seen in motors and are often sufficient for qualitative description of more complex behavior. One further important insight that should be gained from the standing modes is the concept of "mode structure". This relates to the spatial distribution of the oscillatory behavior. Pressure oscillations in a first axial mode may be severe at the ends of the cavity, while there will be no oscillations at all midway between the ends. This is illustrated in Fig. 2.8, which shows the distribution of pressure amplitude with longitudinal position for three longitudinal modes. The locations of maximum amplitude are called "antinodes" and the locations of zero amplitude are called "nodes". Evidently one would not detect the presence of an oscillation if the pressure detector were located at a nodal point. With longitudinal modes this is not usually a problem,

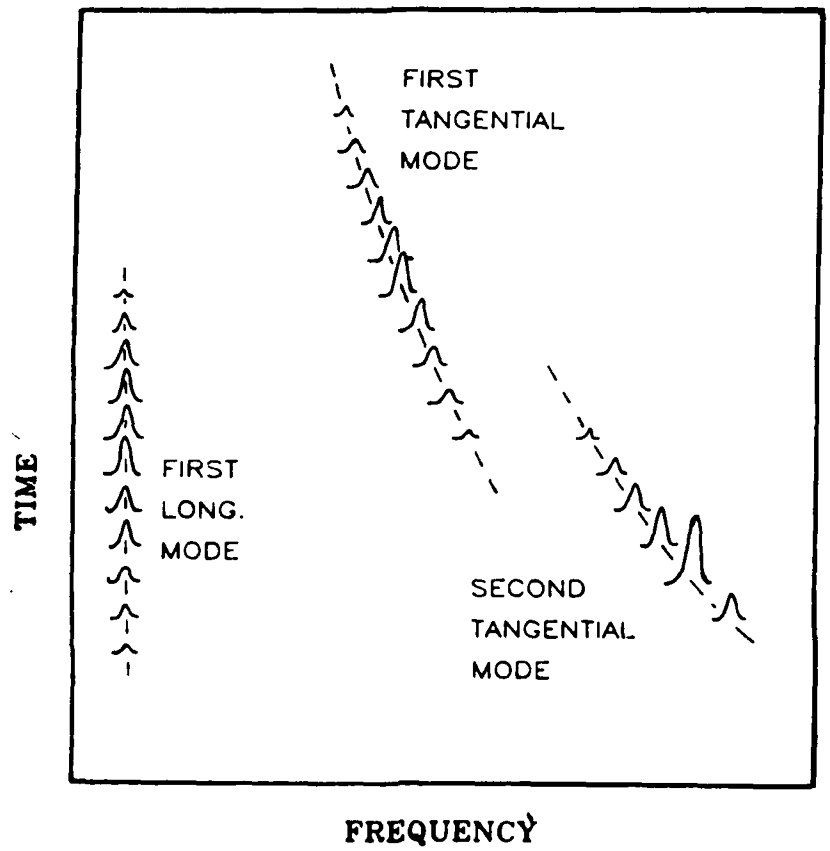

Fig. 2.7 Medal analysis of pressure oscillations during an unstable test firing.

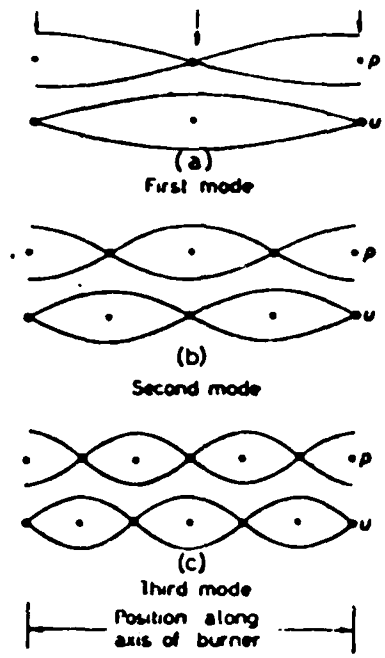

Fig. 2.8 Amplitude of oscillation vs location in the cavity for longitudinal mode oscillations (a cylindrical cavity with closed ends is assumed in the figure, and is a reasonable approximation for motors of simple geometry and length to diameter ratio greater than 3 or 4).

because the pressure transducer is located on the forward cavity wall where pressure amplitude is a maximum. It is much more difficult to get a transducer at an antinode of a transverse mode (and be assured that the antinode doesn't wander away) (Fig. 2.9).

Relative to combustor instability problems, it should be noted that the acoustic mode structure determines the nature of the oscillatory environment at different locations of the burning surface. For a particular acoustic mode, some regions of the surface will be exposed to strong pressure oscillations, but relatively little oscillatory motion of the adjoining gas field (regions near pressure antinodes). At the same time at other locations on the burning surface (near pressure nodes) there will be relatively little pressure oscillation, but the gas oscillations parallel to the burning surface may be large (the pressure mode is a velocity antinode, as shown in Fig. 2.8). In solving stability problems, it is necessary to examine the response of combustion at each site on the burning surface to its own particular oscillatory flow environment, and the response at all the sites must be combined to determine the net effect of combustion on a given mode of oscillation. The procedures for this are described in Chapter 8. In Chapter 4, the nature of the combustion response to oscillations in the flow environment is described in a relatively elementary way, with more complete description in Chapter 5.

2.5 Dynamic Combustion Response

When a quantity of solid propellant expands during conversion to gaseous combustion products in the combustion zone, it does work on the gas already in the combustor, causing the motion of the gas toward and out of the nozzle. Under normal conditions, this is a continuous process. A disturbance in gas evolution rate means a fluctuation in the rate of work on the gas field, which leads to a disturbance having a definite disturbance of energy in the gas motion from the location of the combustion disturbance. Such a disturbance is typically manifested by a pressure wave emanating from the site of the combustion disturbance. The combustion zone over the entire burning surface is

(Figure in preparation)

Fig. 2.9 Distribution of pressure amplitude for some transverse modes of a circular cylinder (curves of constant amplitude are shown).

exposed to these propagating flow disturbances, and the combustion rate can be disturbed over a large part of the burning surface when flow disturbances are present. In short, a flow disturbance can stimulate a combustion disturbance, which can reinforce the flow disturbances. This is called the "dynamic combustion response", and is the heart of the combustion instability problem. Understanding the practical problem requires that one know the nature of the flow disturbances that occur in the region of the combustor where concentrated reaction occurs (usually near the propellant surface), and also know how the combustion responds to these flow disturbances. Aside from a general comment on the nature of the combustion-flow interaction, the following will explain the phenomenon by an example involving relatively simple interaction. The general comment is a three-part one: 1) the flow disturbances can be very complex and can be dependent on location in the combustor, 2) the combustion response is very complex and dependent on the nature of the local flow disturbance, and 3) the state of knowledge of both the flow disturbance field and the combustion response is still rather primitive. Understanding is somewhat better for the special case of combustion response to pressure waves that are perpendicularly incident on the combustion zone, and that special case will be used here to describe concepts of dynamic combustion response.

If one views the combustion zone and flow field as one-dimensional, with a well-defined outer boundary (Fig. 2.10), then the work done by the combustion zone on a perpendicularly incident pressure wave that is produced by a cavity oscillation is commonly related in acoustic theory to the ratio of the oscillation of velocity outward from the combustion zone to the oscillation in pressure experienced by the combustion zone.

$$A_b \equiv \gamma(u'/\bar{a})/(p'/\bar{p}) \qquad (2.2)$$

p' is the oscillation in pressure about its mean value $\bar{p}$ and u' is the oscillation in velocity about its mean value $\bar{u}$. The ratio of specific heats, γ, is included in the definition of A_b in "anticipation" of convenience in later analyses. A_b is referred to as the specific acoustic admittance of the

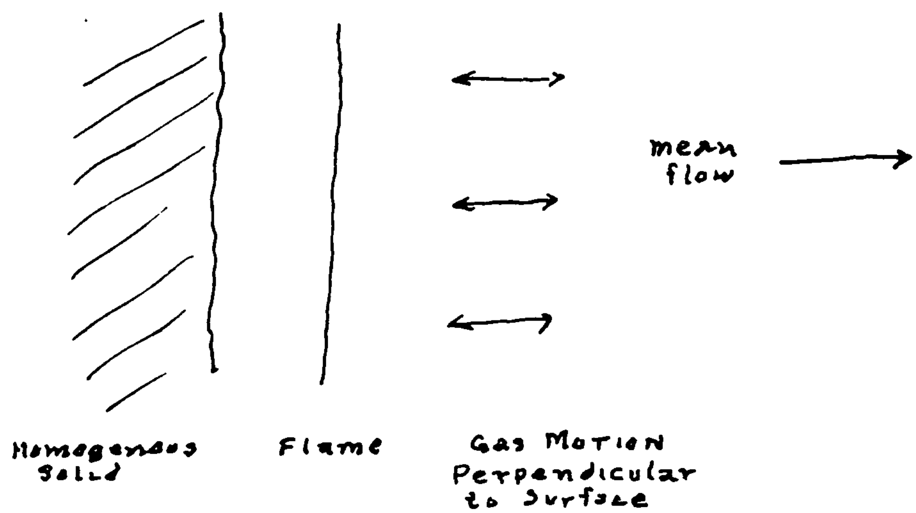

Fig. 2.10 Combustion-flow interaction for a one-dimensional system.

combustion zone. In the classical acoustic analyses of combustor stability, the admittance is a boundary condition for solution of the equations for the cavity oscillations. For the present purposes, it is desirable to relate A_b to other properties of the oscillating combustion zone. By expressing the mass conservation equation in small perturbation form,

$$m = \rho u = (\bar{\rho} + \rho')(\bar{u} + u') = \bar{m} + m' \tag{2.3}$$

where ρ', u' and m' are small oscillations about the mean values $\bar{\rho}$, $\bar{u}$ and $\bar{m}$. The perturbation terms must (to first order of approximation) satisfy the equation

$$\frac{m'}{\bar{m}} = \frac{\rho'}{\bar{\rho}} + \frac{u'}{\bar{u}} = \frac{\rho'}{\bar{\rho}} + \frac{u'}{\bar{a}}\frac{1}{\bar{M}_b} \tag{2.4}$$

(all variables will be used here as referring to conditions at the outside edge of the combustion zone, with velocities perpendicular to the surface; $\bar{M}_b$ is the mean Mach number there)

If a mass response function, R_p, is defined as

$$R_p = \gamma(m'/\bar{m})/(p'/\bar{p}) \tag{2.5}$$

then Eq. 2.2, 2.4 and 2.5 can be combined to give

$$A = R_p - (\rho'/\bar{\rho})/(p'/\bar{p}) \tag{2.6}$$

and if a perfect gas law $p = \rho RT/\mu$ is assumed, this can be written

$$A = R_p + \frac{T'/\bar{T}}{p'/\bar{p}} - \frac{\mu'/\bar{\mu}}{p'/\bar{p}} - 1 \tag{2.7}$$

where T' is the temperature oscillation at the "admittance" surface, and μ' is the oscillation in molecular weight.

This expression gives some idea of what must be known in order to understand the response of the combustion zone to an incident pressure oscillation, p'. Keep in mind that p', T', μ', and R_p (the relative oscillation in mass rate) are oscillating quantities that do not necessarily oscillate in phase with each other. Since it has thus far been extremely difficult to measure R_p, T', or μ' oscillations, A_b is usually determined by either analytical modeling of the dynamic response of the combustion zone for R_p, $T'/\bar{T}$ and $\mu'/\bar{\mu}$ or by experimental estimate of A_b from its effect on combustor pressure oscillations. The problem of analytical modeling is discussed in Chapter 5, and the experimental methods involving combustor oscillation are discussed in Chapter 11. Also mentioned there are some relatively recent efforts to measure the oscillations μ' directly.

Looking further at Eq. 2.7, it is usually assumed that the term $(T'/\bar{T})/(p'/\bar{p})$ is divided into two parts

$$(T'/\bar{T})/(p'/\bar{p}) = \frac{\gamma-1}{\gamma} + \frac{\Delta T'/\bar{T}}{p'/\bar{p}} \tag{2.8}$$

where $(\gamma-1)/\gamma$ is a portion of the oscillation corresponding to isentropic relations of T to p and $\dfrac{\Delta T'/\bar{T}}{p'/\bar{p}}$ is the part of the real oscillation different from the isentropic part. Then Eq. 2.7 becomes

$$A = R_p - \frac{1}{\gamma} + \frac{\Delta T'/\bar{T}}{p'/\bar{p}} - \frac{\mu'/\bar{\mu}}{p'/\bar{p}} \tag{2.9}$$

The terms involving $\Delta T'$ and μ' are not usually rigorously modeled in analyses (μ' is usually neglected without acknowledgment), and different models give different results. However, R_p is ordinarily the dominant term, and is the object of many analytical models (Ref. 2.2-2.4). Examples of such results are shown in Fig. 2.11, where R_p is shown as a function of frequency for different values of two principal parameters in the model.

fig. incomplete

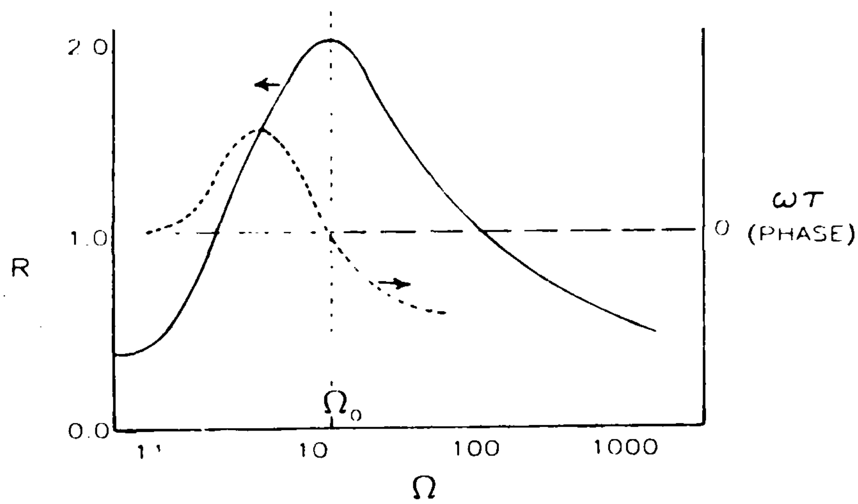

Fig. 2.11 Dependence of pressure-coupled response (R_p) on nondimensional frequency and model parameters A and B (See Ref. 2.2).

In Fig. 2.11, the two parts of the figure show the "real" and "imaginary" parts of R_p, a terminology that reflects the fact that complex variables were used to represent the oscillating quantities. The real part corresponds to the magnitude of the component of the mass oscillation that is in phase with pressure, and the imaginary part indicates the magnitude of the component 90^o out of phase with pressure. Stability analyses show that in most situations the component in phase with pressure is the part responsible for driving of the oscillation (See Chapter 8).

Looking at Fig. 2.11, the abscissa is a non-dimensional frequency

$$\Omega \equiv \frac{\alpha\omega}{\bar{r}^2} = \frac{\alpha}{\bar{r}^2}(2\pi f) = (2\pi \frac{\alpha}{\bar{r}^2})f \qquad (2.10)$$

where $\alpha/\bar{r}^2$ is the thermal diffusivity of the solid propellant divided by the square of the mean burning rate of the propellant ($2\pi\alpha/\bar{r}^2$ is typically of order 10^{-2} sec). In Fig. 2.11a, the value of $R_p^{(r)}$ increases with frequency to a maximum around 1000 Hz and drops off at higher frequency. The parameters A and B have physical meaning in the analytical models (e.g., A is related to the activation energy of the surface decomposition reaction), but the values cannot be determined unambiguously, and are usually chosen to yield the best fit with experimentally determined values of $R_p^{(r)}$, as illustrated in Fig. 2.12. The primary value of analytical models has been to a) better understand dynamic combustion response, b) provide an extrapolation formula for experimental data, and c) help in understanding scaling laws (taking into consideration also that frequency is inversely proportional to dimensions). From the form of the response function curves, it is evident that there is a frequency range in which stability is more likely in the sense that $R_p^{(r)}$ and hence, A_b and acoustic driving tend to be large. The figures also show that the frequency range in question is strongly dependent on mean burning rate through the dependence of Ω on $\bar{r}$. As will be seen in Chapter 5, analytical modeling of combustion response is still under development, with limited capability to encompass the wide range of propellant behavior encountered in practice. The

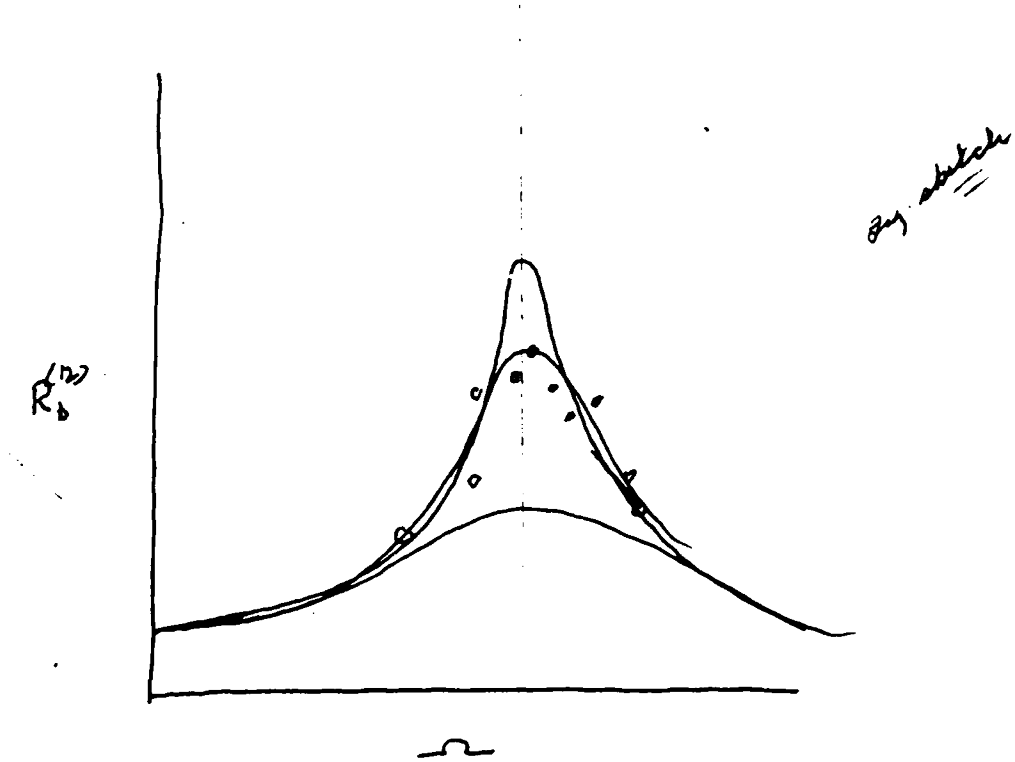

Fig. 2.12 Comparison of experimentally determined values of $R_p^{(r)}$ with theoretical curves.

measured response function trends are found to be dependent on propellant variables and flow environment variables whose roles are not encompassed in the models. These are areas of ongoing research, and there is much more information available than implied above. However, the elementary analyses serve the present purpose of illustrating the manner in which combustion responds to flow disturbances and amplifies these disturbances. In the next section, the consequence of this behavior is examined in the context of the combustor environment.

2.6 Combustor Stability

In the preceding sections the nature of the oscillatory motions of the gas in the combustor cavity has been described in a qualitative way, and the concept of responsiveness of the combustion to the flow disturbances has been introduced. Since disturbed combustion can produce flow disturbances and flow disturbances can cause combustion disturbances, one may anticipate that the combined disturbances might, under some conditions, reinforce each other and produce growing disturbances. The particular conditions are those under which the combustion-generated flow disturbances are suitably phased to reinforce the initiating flow disturbances, and the sources of damping of flow disturbances are not too high. Because of multiple reflections of pressure waves, the disturbances are ordinarily periodic and tend to occur in the less heavily damped natural cavity modes (whichever ones are more strongly reinforced by combustion response and less heavily damped by viscous and radiative loss of oscillatory energy). When the combustion reinforcement of a particular mode is stronger than the damping of the oscillation, the oscillations will grow with time, and the mode is said to be unstable. As the amplitude of oscillation increases, the combustion reinforcement increases as does the damping. In the usual case, the excess of combustion reinforcement over damping grows with amplitude, so the amplitude increases at an increasing rate (Fig. 2.13) and very large amplitudes can be reached.

To understand unstable behavior better, it is helpful to describe the behavior in terms of energy in the oscillation of a mode of interest.

Fig 2.13 (Sketch)

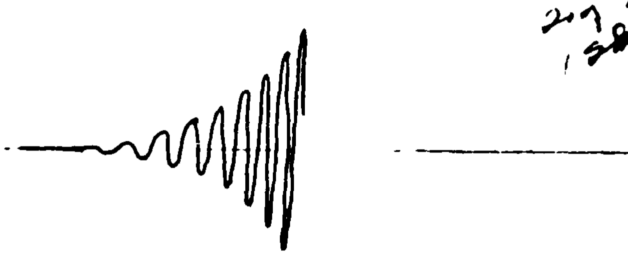

Fig. 2.13 Example of divergent oscillations due to excess of combustion reinforcement over damping.

Addressing a specific geometry and mean flow situation corresponding to a particular time during burning of the propellant charge, the oscillatory motion of a specific mode at a specific amplitude can be characterized by a specific energy of the oscillation, E. The combustion response to the oscillation contributes energy to the oscillations at a rate designated by $\dot{E}_c$, and damping processes dissipate energy at a rate $\dot{E}_d$, where

$$\dot{E}_c + \dot{E}_d = dE/dt$$

For the sake of description, assume for the moment that E may have any value (which would depend on previous conditions), and consider how $\dot{E}_c$ and $\dot{E}_d$ would depend on E. At moderate amplitudes of oscillation (as indicated by the value of E), $\dot{E}_c$ and $\dot{E}_d$ are typically proportional to E, so that $\dot{E}_c$ and $\dot{E}_d$ vs E are typified by the straight lines in Fig. 2.14 (this corresponds to a response function independent of amplitude, and similar linear dependence of damping forces on amplitude). In the illustration in this figure, $\dot{E}_c$ is shown as larger than $-\dot{E}_d$, which means that (since $\dot{E}_d$ is negative) $E_c + E_d = dE/dt > 0$, i.e., the oscillations are growing as in Fig. 2.13. Further, dE/dt is larger for large E, corresponding to more rapid growth of oscillations at large amplitude.

Under different conditions the $\dot{E}_c$ curve may be below the $-\dot{E}_d$ curve; under such conditions E would decrease, or, in the absence of oscillations, none would develop. This would correspond to stable conditions. During the burning of a specific motor, conditions may change from stable to unstable and/or the reverse, so oscillations in a particular mode may develop and sustain only during a certain part of the burning period (Fig. 2.7). Modifications in design would be aimed at causing the $\dot{E}_c$ curve in Fig. 2.14 to be below $-\dot{E}_d$ for all times during burning, under all normal operating conditions of the motor. The problem of stability analysis involves quantitative evaluation of the values of $\dot{E}_c$ and $\dot{E}_d$ for all times during burning of the motor, for all modes of oscillation, over all operating conditions of the motor (e.g., temperature). To the extent that the curves in Fig. 2.14 are straight lines, it is sufficient to show that the slope of the $\dot{E}_c$ curve is lower than the slope of the $-\dot{E}_d$ curve

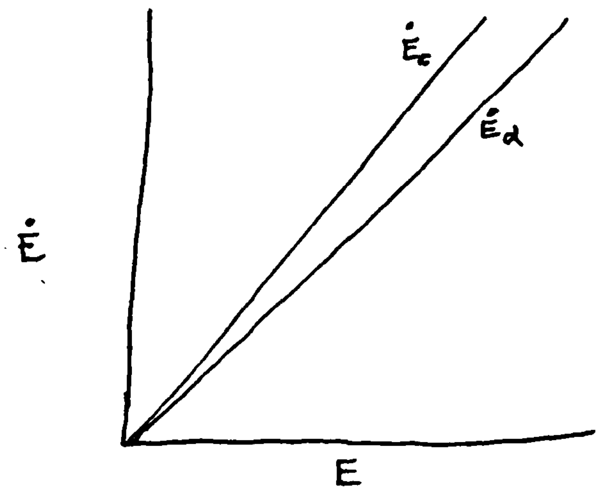

Fig. 2.14 Illustration of stability argument by comparison of combustion energy gains and energy losses to flow oscillations (the ordinate is oscillation energy change per second, shown as a function of oscillation energy level). Example is for linear system; with $\dot{E}_c > -\dot{E}_d$, unstable:

at $E \approx 0$ for all conditions. This generally is not a very easy thing to do, because the calculations are tedious, the conditions to be considered are numerous, and the input data on combustion response and damping are only poorly known. However, the analyses are extremely useful for estimating the conditions most likely to yield oscillatory behavior, what mode (s) might be unstable, and how sensitive stability is to relevant design and propellant variables. Such information is helpful in guiding test work, and in design to avoid or correct instability. These are issues discussed at length i later chapters.

The foregoing discussion was designed to help the novice understand why oscillations may occur. The description corresponds closely to a concept related to "linear" stability theory. This is reflected in the linear dependence of $\dot{E}_c$ and $\dot{E}_d$ on E, and goes back to the use of linearized forms of governing conservation equations, which are applicable only at small amplitudes of oscillation. There are important aspects of observed combustor instabilities that cannot be described by linear theory, which are explained qualitatively here, and examined in more detail in later chapters. The five qualitative aspects of observed behavior that are most conspicuous are:

a) At large oscillation amplitudes, the mean burning rate is often modified (with corresponding changes in mean pressure as noted in Fig. 1.5).

b) At large amplitudes the oscillations level off, indicating that $\dot{E}_c$ and $\dot{E}_d$ become equal at some value of E (Fig. 2.15a).

c) In some systems, $\dot{E}_c < -\dot{E}_d$ at low amplitude (low E), but oscillations will grow if they are stimulated independently at large amplitude (meaning that $\dot{E}_c$ becomes larger than $-\dot{E}_d$ at large values of E (Fig. 2.15b).

d) Under certain conditions, the oscillations develop into shock-like waves that do not behave like any combination of the simple cavity modes that are observed at low amplitudes (Fig. 2.16).

e) In some cases, the excitation of oscillations involves conversion of mean flow energy to oscillations by action of viscous forces (e.g.,

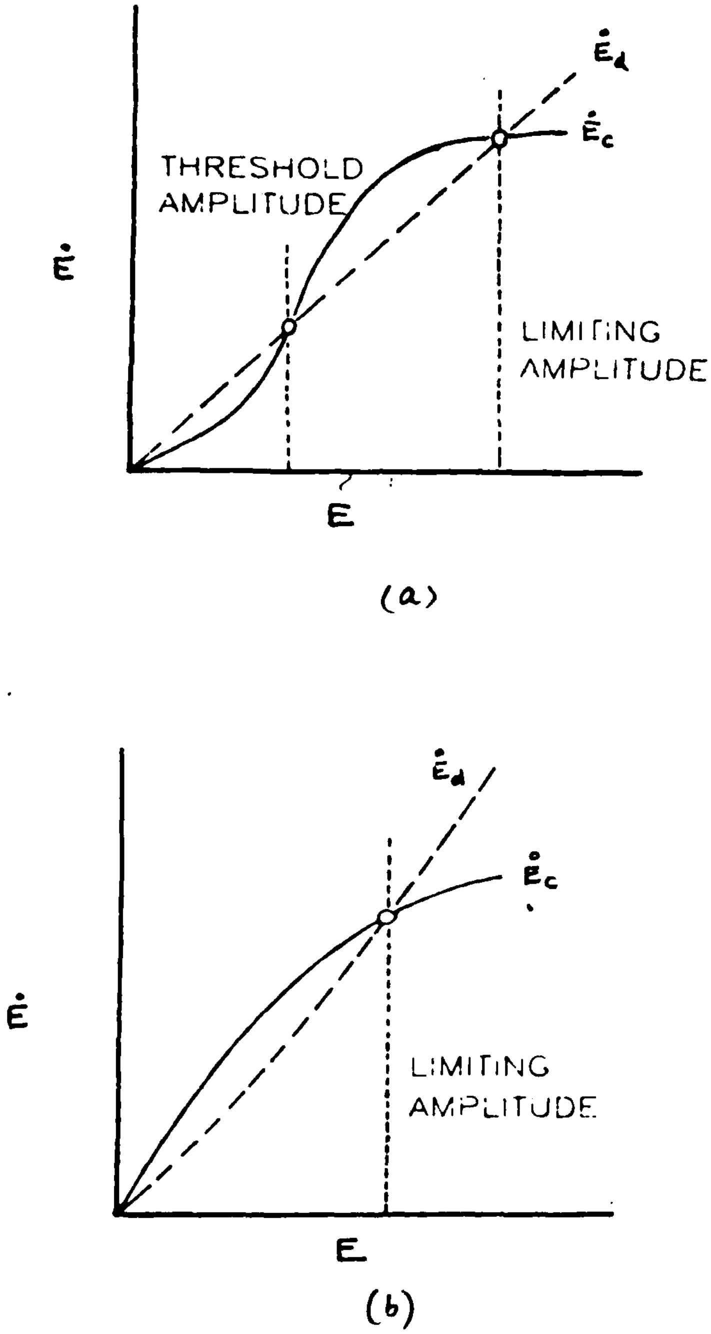

Fig. 2.15 Energy balance argument of Fig. 2.14 extended to nonlinear domain:

a) trends of $\dot{E}_c$ and $\dot{E}_d$ leading to a limiting amplitude, and

b) trends of $\dot{E}_c$ and $\dot{E}_d$ yielding stability to small amplitudes, but growing oscillations if the system is pulsed to large amplitude.

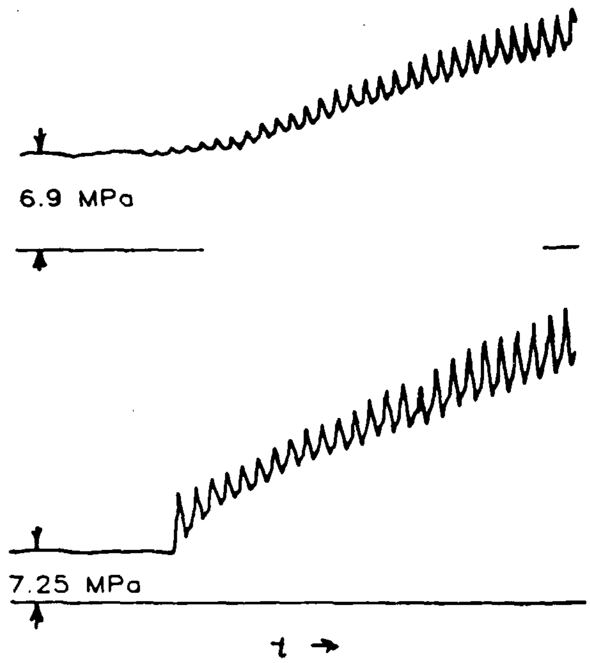

Fig. 2.16 Sketch of oscillations resulting from sharp-fronted wave.

via vortex behavior) rather than by, or in addition to, combustion oscillations (Ref. 2.5).

Of the above aspects of large amplitude behavior, item a) does not ordinarily contribute directly to the growth or decay of oscillations, but (b-e) do contribute, and will be discussed in detail in Chapters 8 and 10. The behavior in (b) (amplitude limiting) is illustrated in Fig. 2.15a in terms of $\dot{E}$ dependence on E. The combustion contribution to dE/dt ceases to be proportional to E at large E, and at some value of E, $\dot{E}_c$ becomes less than $-\dot{E}_d$. This indicates that oscillations would stop growing at some limiting amplitude, and change thereafter only as the $\dot{E}$ vs E curves change with changing combustor geometry and mean flow field. If this type of nonlinearity did not come into play, oscillations would grow to destructive amplitude in most episodes of instability.

The type of nonlinearity in c) above is often involved in longitudinal mode instability, and was described by an example in Chapter 1. In terms of the $\dot{E}$ vs E diagram, the slope of the $\dot{E}_c$ curve is lower than the slope of the $\dot{E}_d$ curve at low amplitude (Fig. 2.15b), but at intermediate amplitude, $\dot{E}_c$ becomes larger than $\dot{E}_d$. Then, growing oscillations can occur if they are started at large enough amplitude by (for example) discharge of debris through the nozzle. Such a system is "linearly stable", and may appear in tests to be stable until some spurious condition leads to instability. One of the objects of ongoing research is to identify the nonlinear processes that give rise to this kind of instability (Ref. 2.6, 2.7). In addition, methods of artificially pulsing suspect systems have been used to determine the presence of a nonlinearly unstable condition and to obtain such behavior for study (Ref. 2.8-2.11). Understanding of this type of behavior has been impeded by its complexity and its dependence on the whole combustor flow field (and the resulting high cost of experimental research).

The sharp wave front behavior (Fig. 2.16) referred to in e) is often manifested during the pulsed instability described above. The presence of such behavior is characteristic of nonlinear behavior, and implies that the behavior cannot be fully described on the basis of linearized analyses and simple cavity

mode oscillations. Considerable study has been devoted recently to development of analyses that would explain the instability threshold, wave shape and limiting wave shape and amplitude. However, from the practical viewpoint, the problem is to avoid this type of instability, either by avoiding pulses, or by assuring a threshold so high that otherwise tolerable flow disturbances would correspond to less than threshold level. The detailed discussion in Chapter 10 invludes this subject.

2.7 Classes of Combustor Instability

The designer is always in need of some simple rules to use in dealing with problems, and combustion instability is no exception. While nature is not very cooperative in this matter where combustion instability is involved, past experience has shown that instability behavior and causative conditions are strongly dependent on oscillation frequency. Following the lead of an earlier effort (Ref. 2.12, 2.13), instabilities are classified below into three frequency ranges and the unique features of instability in each range are described. This description should prove useful provided the reader recognizes that there is nothing fundamentally distinguished by frequency alone, and the instability characteristics cannot be classified uniquely by frequency. With this proviso, one might classify instabilities as low, intermediate, and high frequency. In this categorization,

1. Low Frequency Instability is in the range of 10 - 400 Hz, is observed mostly in large motors, usually in longitudinal modes, and usually with aluminized propellants. Below about 200 Hz, oscillations have been nearly sinusoidal. Vortex processes are sometimes an important contributor to the oscillations, especially in segmented motors and in configurations where the mean flow experiences abrupt velocity changes along the flow path to the nozzle. Two phase flow damping can be relatively low in this low frequency range, and is strongly dependent on the size of Al_2O_3 droplets formed during combustion of the aluminum ingredient.

2. Intermediate Frequency Instability. This includes behavior typical of frequencies from about 200 Hz to about 1500 Hz, and typically involves longitudinal modes of oscillation with either aluminized or nonaluminized propellants (instances with aluminized propellants are usually below 800 Hz). This is the set of conditions under which pulsed instabilities and sharp-fronted wave forms are most likely to be found. However, oscillations may start from low amplitude. The amplitude can become very large, and is often manifested as strong vibrations in the rest of the flight system. The fact that the gas oscillations are in a direction parallel with the mean flow and to much of the propellant burning surface appears to be a major factor in the characteristics of this type of instability.

3. High Frequency Instability. This includes behavior in the frequency range above 1500 Hz, and usually corresponds to transverse mode oscillations. Frequencies as high as 60,000 Hz have been recorded. The main problem is with tangential mode oscillations in motors with diameters of 0.4 meters or less. Because of two phase damping, HFI rarely occurs with aluminized propellants. Instability seems to depend primarily on pressure-coupled combustion response, which can be characterized in laboratory scale firings. Because of the complex cross-sectional shapes used for many propellant charges, the acoustic modes and their stability are difficult to calculate, but change in cross sectional geometry is often an effective way of suppressing instability in HFI.

Other ways of classifying instability include pulsed vs nonpulsed, velocity coupled vs pressure coupled, nonlinear vs linear, vortex driven vs combustion driven, with or without mean pressure rise, or classification by acoustic mode. Since no classification method serves all needs, and each overlaps the others in some measure, it is not useful to dwell on classification except as a qualitative introduction to the subject. Table 2.1 summarizes some of the above descriptive classification categories as they pertain to the LFI, IFI, HFI classification system. It should be understood that the cross-categorizations represent trends rather than rules.

Summary

In this chapter, the physical processes that lead to combustion instability are described in qualitative terms, and some commentary on the state of knowledge is provided. This description may help the nonspecialist to understand the problem and communicate with the specialist. The chapter ends with a classification of combustor instabilities according to frequency of oscillation, and relates three frequency ranges with other features of behavior, design, and propellant.

Table 2.1 Some Rash Generalizations about Trends of Combustor Instability

	LFI	IFI	HFI
Frequency	0 - 400	200 - 1500	1500 - ?
Mode	Longitudinal, Bulk	Longitudinal	Transverse
Coupling	Pressure, "Velocity"	Pressure, "Velocity"	Pressure
Propellant*	Aluminized, (Nonaluminized?)	Aluminized, Nonaluminized	Nonaluminized
Spontaneous or Pulsed	Spontaneous	Spontaneous or Pulsed	Spontaneous
Severity	Mild, except in some bulk mode cases	Mild to severe, severe *in pulsed* instability	Mild to severe
Mean Rate Rise**	Mild	Mild - Strong	Strong
Coupling to Vehicle	Strong	Strong	Mild

* Some propellants are never unstable. Aluminized propellants are stable in HFI because of two phase flow damping.

** Strongly dependent on severity of oscillation, strong with low burning rate propellants.

Chapter 3

GUIDANCE IN MISSILE SYSTEM AND MOTOR DESIGN

3.1 Introduction - The Risk

Combustor instability is a complex phenomenon, the control of which is not usually susceptible to quantitative design. Since it is encountered in only a minority of development programs, the first reaction of many design teams is to gamble that there will be no problem (a gamble often taken without explicit decision, but rather by doing very little in the way of avoidance measures). Choices of charge geometry and propellant are made to meet other design criteria. Even if an early decision is made to act to avoid combustor instability, the design criteria are so qualitative in nature that they may be ignored in the trade-offs for other more clearly defined competitive design requirements. Until the prediction of combustor stability is on a more quantitative footing, the treatment of the problem in development programs will probably continue to be a secondary consideration unless it is encountered as an unacceptable reality during developmental testing. In hindsight, it is clear that this is a bad policy, as encounters in testing (e.g., full scale static firings or flights) or later in operational service can require very costly remedial measures, or degradation of system performance. However, it is less clear what measures should be taken early in development, and it is the purpose of this chapter to offer some guidance on this question.

The presence of a combustor instability problem in a development program ordinarily becomes evident during developmental testing, and in cases of severe oscillations, remedial measures are sought at that time. Detection early in the program provides a better opportunity for remedial measures. As in the examples in Chapter 1 and Ref. 3.1, detection or remedial efforts later in the program can be very costly. In this regard, cases of less severe oscillation are sometimes deemed tolerable and go into service. However, cases that appear to be innocuous sometimes are found to cause unacceptable functioning of other vehicle systems (usually, but not always, as a result of associated vibrations). Such problems may not be manifested until well into a production program, when some changes in the vehicle or in the propulsion system lead to either greater sensitivity to vibration or a change in the nature of the combustor oscillations. Such episodes

have been traced to changes in suppliers of vehicle components (vibration specifications rarely encompass vibration environments induced by combustor oscillations). Other episodes have been traced to changes in suppliers of propellant ingredients, or to minor changes in charge configuration made to solve production problems. Obviously, encounters with unacceptable combustor instability-induced problems during a production program can be very costly, causing production delays and uncertainty regarding the adequacy of previous production or even rejection of products. Given the potential cost of instability problems after production has begun, it is important to eliminate the problem during development. For the program in which a calculated risk of instability problems remains at the start of the production program, special measures should be taken to fully assess and contain the problem.

3.2 How Much Does the Design-Development Engineer Know?

Developing and implementing a strategy for avoiding combustor instability-related problems is not one of the requirements that automatically appears on the program manager's "check list", and most propulsion system engineers and propellant chemists have only a superficial knowledge of the problem. An awareness of this situation is thus the first prerequisite of a strategy for avoidance. The accumulated knowledge is, by now, sufficient for strategy planning, but the intimidating body of literature rarely addresses this subject. The balance of this section will address this subject in a manner aimed at serving program managers. It will, hopefully, also provide a lead-in for motor designers and and propellant chemists to other parts of the report that may be useful to them.

3.3 Considerations Early in Development Program

During a development program, a progressive process of analysis and design decisions occurs, guided by the preliminary performance goals and cost-safety constraints. The further this process goes, the more limited are the options for avoidance of instability problems without reversal of previous design and propellant choices and program commitments. If instability is detected late in a development program, the level of commitment to design and the pressures of time and cost may lead to that unhappy decision to "live with instability" in the

final system. Under such "tardy circumstances" this may be the appropriate decision. However, this represents an absence or failure of early strategy. Further, it carries with it the responsibility to develop an instability management program throughout flight qualification, production, and service. Since almost no development program has ever accepted that responsibility, the record shows primarily the episodes where the failure to do so caused major program problems. Early strategy to address the instability problem can lead to avoidance of major program problems and match the instability considerations to the particular program.

The first priority in a planning strategy is:

a) a preliminary determination of the risk of instability with the propellants and designs under consideration,

b) a judgement regarding the cost of modification and testing in the event instability is encountered, and

c) a determination of the sensitivity of the flight vehicle to instability-induced malfunction.

Regarding a), there are combinations of designs and propellants that pose low risk of instability in some motor sizes and configurations, some combinations that pose high risk, and some combinations that are quite unpredictable. The degree of sophistication of the instability-avoidance aspects of the program should be estimated early in program planning, as soon as motor configuration and propellant type has been narrowed down. A program manager would do well to call in a combustion instability specialist with both fundamental and development program experience to assist in risk evaluation and commensurate program planning.

Regarding b) above (cost of empirical remedy of instability problems), it may happen in a "small motor" development program that motor fabrication and testing costs are low enough so that any instability problems can best be corrected by direct evaluation (using full scale motor firings) of judicious changes in propellant, charge configuration, or oscillation damping devices. It may even be practical to assess the margins of stability by pulse testing or testing with other destabilizing modifications. In such a development program, planning strategy would be aimed more at early detection and remedy, and less at complicated stability analyses and prevention. On the other hand, some programs involve motors that are very costly to produce and test. In such a program, much more reliance should be put on evaluation of stability characteristics of

propellants (laboratory scale tests) and analytical-computational prediction of combustor stability (the government sometimes requires bidders for development contracts to indicate what testing and analysis will be proposed). Evidently, the strategy for dealing with a combustion instability risk may be quite different, depending on the cost of motor testing.

Regarding c) above (susceptibility of the flight system to impairment of function by combustor instability), there are simple systems in which the effect of instability can be forecast and the seriousness assessed. That assessment may indicate that instability would produce no unacceptable adverse system performance (rarely true if instability is severe). This would be a basis for a somewhat "relaxed" attitude regarding combustor instability. In more complex propulsion and flight systems, an advance assessment of adverse effects of combustion instability may be prohibitively difficult. In such a system, it would be advisable to devote more attention to the combustion instability problem. The consequences of failure to address this situation can lead either to flight problems or to the necessity to "harden the bird" (detailed design and construction to function in the adverse vibration environment). Either alternative is a costly alternative to a timely and successful program for prevention of instability earlier in the development program.

The foregoing considerations (of risk of instability, potential complexity of corrective measures, and vulnerability of the flight system to instability-induced malfunction) are basic to a strategy for the problem. From these considerations it may be decided that instability is an unlikely problem, an easily fixable problem, or a problem with minimal adverse effects, or any combination of these. Such conclusions typically lead to subsequent neglect of the problem, with reasonable justification. On the other hand, a less optimistic preliminary judgement should lead to further strategy for containment of the problem. The balance of this chapter will address some of the technical aspects of combustor instability in the general terms needed for strategy planning.

3.4 Design and Propellant Considerations

There are many combinations of motor-charge design and propellant composition for which combustor instability has never been observed. Indeed, there are some types of propellant that seem to be immune to instability, such as those using potassium perchlorate or ammonium nitrate as oxidizer. It is also

observed that propellants containing more than about 10% aluminum powder as a fuel ingredient are rarely or never unstable in small rocket motors. On the other hand, there are some propellants that can cause instability in all size motors. Unfortunately, these differences are not usually fully understood. Further, there seems to be a tendency for the stable propellants to be ones of rather low performance (i.e., low I_{sp}, as with AN and KP propellants). While there is no way to reduce this complex problem down to simple generalizations without risk of real-life exceptions to the generalizations, strategy planning has to be based on general trends and recognition of risk. It is in this context that some general qualitative trends are described here.

Instabilities ordinarily occur in the lower frequency transverse modes and longitudinal modes of the combustor cavity. In large motors, these modes correspond to relatively low oscillation frequencies. A cavity with a characteristic lateral dimension (L) of 1 meter will have a first transverse mode frequency (f) of roughly

$$f = a/2L = (1200 \text{ m/sec})/2 \times 1 \text{ m}$$

$$= 600 \text{ Hz}$$

and a first longitudinal mode frequency of perhaps 1/3 to 1/10 this value. The dynamic response of most propellants is very different in this low frequency range than at higher frequencies, and the damping characteristics of the propellant reaction products can also be strongly frequency dependent. One profound consequence of this is the failure of small scale tests to evaluate the stability of full scale motors. Another consequence is a rather significant difference in stability trends in large and small motors. Based on experience, large motors are less prone to combustion instability. In very large motors, such as the Titan IIIC and Space Shuttle booster motors, this is probably due to low dynamic response of the combustion at the low characteristic frequencies. In somewhat smaller sizes (but still large), stability is suppressed by damping processes associated with the condensed phase Al_2O_3 reaction products typical of such motors. However, combustion response to flow oscillations can be significant at frequencies above about 200 Hz (characteristic dimensions less than approximately 3 m) and episodes of unstable combustion become more common (and sometimes critically dependent on the damping characteristics of the Al_2O_3

products, as in one of the examples in Chapter 1).* Since the higher frequency transverse modes benefit more from the two-phase flow damping than do axial modes, the large motor instabilities tend to be more often observed in longitudinal modes. This is particularly true of booster motors, which have high length-to-diameter ratios (and aluminized propellants).

In the frequency range 600-1800 Hz corresponding to characteristic dimensions of 1 m to 1/3 m, there is strong competition between combustion response and two-phase flow damping. The system is strongly driven and strongly damped. Stability is relatively less predictable because very substantial uncertainties in both combustion response and damping can easily make the difference between a prediction of stable or unstable conditions. In short, stability depends on the difference of two large effects, neither of which is well determined. With aluminized propellants the trend is to increasing stability as mode frequencies go up. Propellants with 15% of aluminum rarely exhibit oscillations in motors at frequencies higher than above 1500 Hz (characteristic dimension 0.4 m). Thus, tactical rocket motors with aluminized propellants rarely, if ever, show unstable combustion in transverse modes, but are sometimes unstable in lower frequency longitudinal modes.

In applications using nonaluminized propellants, the trends imposed by two-phase flow damping (increased damping and stability at higher frequency) are absent. Since nonaluminized propellants have seen little use in large motors, there is little basis for generalization regarding stability. However, nonaluminized propellants are often preferred in tactical rocket motors, and the dimensions of such motors are typically in the range below 0.3 m (diameter) and 3 m (length). This corresponds to frequencies greater than 2000 Hz (transverse mode) and 200 Hz (longitudinal mode). Instabilities are encountered in both transverse and longitudinal modes in such motors, most often in the transverse modes. There are a wide variety of propellants used in these applications, and all those in common use are capable of producing instability.

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* These trends do not apply to the bulk-mode oscillations that sometimes occur in low L^* motors at frequencies of 10-200 Hz (see Chapter 8).

Control of instability with "smokeless" propellants is accomplished by a variety of methods that are discussed in Chapter 14. For the program planner, it is important to note that there is a relatively high risk of combustion instability in motors of the size used in tactical rockets using propellants selected to minimize condensed phase products. It is also important to note that high frequency transverse mode oscillations are not generally resolved by routine static test instrumentation, so that their presence may go undetected in development programs unless it produces other detectable manifestations, such as the mean pressure shifts noted in Fig. 1.5. Reference may be made to Chapter 13 for information on measurements. As noted earlier, delay in recognition of an instability problem makes correction much more costly and/or difficult. Because of the relatively high risk of instability with smokeless propellants, the program planner would do well to seek guidance of a specialist before settling on a propellant or charge design, and when designing static test hardware and choosing static test instrumentation.

3.5 Design Trade-Offs

Design of rocket motors is a process involving a careful balancing of many competing factors. High performance calls for high energy propellants, light motor cases, and acceptable reliability and safety. High energy propellants are generally more prone to combustion instability than others, and lightweight motors are more vulnerable to instability-induced damage. Similarly, smokeless propellants that are so desirable in some tactical applications are particularly susceptible to combustion instability because of low damping. Many propellant charge geometries that are particularly desirable in terms of either ease of production or attainment of desired ballistic performance are relatively more susceptible to combustion instability. High burning rate propellants are (in theory, and sometimes in practice) more susceptible, especially in high frequency modes. These trends reflect areas where design for attainment of stable performance can be in conflict with other demands on design or propellant, and extra effort may be needed to meet all requirements. Unfortunately, these design trade-offs have not been formalized in simple terms because the trends are not consistent over the range of propellants, designs and operating conditions of interest, and the more detailed trends have not been established. The program planner needs to be aware that his designers are confronted with possible

compromise and complication in design, testing and performance to achieve stable combustion.

3.6 Measurements during Testing

It was noted above that measurement of oscillations calls for special attention to detectors. The past record shows that there is an extraordinary resistance to incorporation of such instrumentation in test programs. There seem to be several reasons of which program planners should be aware:

a) nonrecognition of need,

b) unfamiliarity with methods,

c) unavailability of instrumentation,

d) failure to provide appropriate fixtures in test hardware (e.g., for mounting high frequency response transducers), and

e) fear that transducer or its fixture may be the cause of a motor case failure during a test.

The instrumentation problem is discussed in more detail in Chapter 14. For the purpose of this chapter, it is sufficient that the program manager understand that there are many practical reasons why occurrence of oscillations may not be detected, but the failure to do so can lead to tardy recognition of a problem, and the by now familiar penalties of a tardy remedial program or "live with it" decision.

Summary

This chapter is intended to give some insight into the impact of combustion instability on motor design and missile system development. The content is addressed primarily to readers who are concerned with planning strategy for a development program. It is noted that propulsion system designers and propellant chemists are rarely knowledgeable concerning combustion instability, and that some overt management effort may be required to assure timely consideration of the problem. It is noted that the problem should be addressed and solved early in the development program in order to avoid very costly encounters later. The relative likelihood of instability-related problems is described in terms of the type of missile system, size of motor, and type of propellant. Some comments are made regarding measurements of oscillations during development testing, comments

addressed to program planners and managers. Nearly everything in this chapter is treated elsewhere in the book in more detail, and the designer will generally find such treatments more useful. The program planner will find further guidance also in Ref. 3.1, and both planner and designer will find help on design and testing in Ref. 3.2 and 3.3.

Rough Draft

Chapter 4

FUNDAMENTALS OF PROPELLANT COMBUSTION

4.1 Introduction

Combustion of solid propellants for rockets has been a topic of vigorous research since the early 1940s, with significant prior work in connection with guns. The research has become increasingly sophisticated since about 1955, and particularly since 1960, because of the growing role of rocket propulsion in military and space applications, and because of concurrent advances in combustion science and experimental methods. The complexity of the propellant combustion process and its diversity among the many propellant systems in use have prevented any definitive quantitative understanding, and research tends to be either a search for qualitative understanding or a quantitative experimental characterization of global combustion trends, such as mean burning rate as a function of pressure, propellant bulk temperature, and ingredient variation. Measurements of global combustion behavior provide both design data and trends that realistic combustion theory must be able to correlate. As was noted earlier, direct measurement of details of the combustion process is usually precluded by difficulties with a hostile measurement environment and the microscopic scale of the key combustion regions. Given this situation, one must anticipate that understanding of oscillatory combustion rests on a complicated combination of information about propellant combustion involving: a) analyses that are chronically oversimplified, b) thermal decomposition measurements of unknown relevance to combustion, and c) observations of global combustion behavior that reveal little direct information about combustion mechanisms. Some insight into this situation can be obtained from a recent book on solid propellant combustion (Ref. 4.1).

In the present book, it is necessary to have a reasonable understanding of the nature of the combustion process (and its diversity) in order to address the oscillatory combustion problem realistically, and the objective of this chapter is to provide that understanding in a way designed to reflect the

particular needs of this book. The section headings indicate the approach, from a description of the propellants themselves to a description of how the individual ingredients behave at elevated temperatures, to a discussion of what is known about the combustion process, and a description of strategies for analytical modeling of steady state and oscillating combustion. Chapter 5 presents the analytical models, and Chapter 7 describes models of the combustion-flow interaction.

4.2 Nature of Propellants and Ingredients

Solid propellants must meet an extremely diverse set of requirements, of which combustion behavior is only one. As a result, any discussion of the state of knowledge of combustion behavior draws from a pool of past work that was heavily constrained by consideration primarily of propellant ingredient combinations and formulations that qualify relative to the many requirements other than combustion behavior. Among those constraining requirements, it is necessary that propellants be energetic but safe, strong but processable, highly combustible but resistant to unintentional ignition. The outcome of such considerations is that propellants are typically materials with relatively hard, rubbery consistency, poor heat conductors, homogeneous "in the large" but often heterogeneous on the 1-1000 micrometer scale. The heterogeneity ordinarily reflects the combinations of an oxidizer and a fuel. The oxidizer is usually a crystalline solid in powder form, and the fuel is usually a polymeric material, which serves also as a "binder" and provides the mechanical integrity of the mixture. Depending on the relative importance of safety and propulsion performance, the binder may be either a synthetic rubber-like material or an energetic material (e.g., nitrocellulose) with an energetic plasticizer (e.g., nitroglycerine). In some applications, the high energy binder is used without the oxidizer, resulting in a homogeneous propellant. In many cases, an appreciable amount of metal powder (usually aluminum) is used as a fuel ingredient. Some of the oxidizers that are used are perchlorate salts (ammonium, potassium, lithium), ammonium nitrate, and nitramine salts (HMX, RDX). Of these, AP and HMX are most common. Propellants with "rubber" binders

require a high oxidizer content in order to achieve maximum propulsion performance (e.g., 90%), a requirement that is in conflict with requirements for processability, mechanical strength and low sensitivity of the propellant. Rubber-binder propellants typically have 10-20% binder. The overall stoichiometry is normally fuel-rich, a property that reduces the tendency for erosion of exposed motor components (but can leave the exhaust capable of combustion in air). The particle size of ingredients is adjusted within limits to control the burning rate of the propellant, but is usually carefully blended to permit effective "packing" in the matrix to yield the highest solids content compatible with acceptable mechanical properties (in the product and during mixing). For these reasons, the particle size distribution is already significantly constrained and, thus, is not fully available for control of combustion behavior.

In combination with the subject matter in Chapter 2, the foregoing can provide some insight into the nature of propellants and complexity of combustion to be expected. However, it should be noted that propellant ingredients differ drastically in their response to the temperature encountered in the combustion zone, and that a good understanding of the combustion requires an understanding of the thermal response of all the major ingredients. This topic is addressed in the following, where it will be noted that the same problems that plague measurement of propellant combustion zone processes are still present, but to a lesser degree, in characterizing the behavior of the individual ingredients.

4.3 Ingredient Decomposition and Self-Deflagration

Background. From the standpoint of decomposition characteristics, propellant ingredients range from metal particles that don't decompose to hydrocarbon binder and some oxidizers that decomposes endothermally, to energetic binders and oxidizers that decompose exothermally and usually self-deflagrate under some conditions. These differences in decomposition characteristics strongly influence the role that each ingredient plays in

propellant combustion. It is not feasible to summarize the large body of pertinent literature on ingredient decomposition here, but some understanding of ingredient behavior is essential to understanding and modeling combustion, and in deciding what decomposition data are relevant to combustion.

Decomposition behavior of propellant ingredients has been studied for a variety of reasons, such as safety of processing and storage, hazard in fire environments, and evaluation of catalysts and stabilizers. It is not yet clear how much of the results of such studies are relevant to propellant combustion processes, although such results are often used as guidance in propellant formulation studies. The uncertainty regarding relevance is due primarily to the low temperatures of decomposition studies compared to propellant surface temperatures. A difference is 50 - 100^{o} C, which is very large when studying complex chemical reactions governed by rate laws with exponential temperature dependence. High temperature experiments are very difficult, precisely because the reaction rates are so high. Controlled heating and quantitative time-resolved measurement is so difficult that little in the way of high temperature data is available. Much of our current understanding of ingredient decomposition rests on the low temperature decomposition results, or back-inference from global observations of self-deflagration and propellant combustion.

One useful experiment for showing qualitative features of ingredient decomposition at moderate temperatures is the differential thermal analysis (DTA) method. In this experiment, a test sample is heated by conduction from an electrically heated sample holder, and the endo- or exothermicity is observed by its effect of sample temperature, measured by a thermocouple. Temperature is programmed upward at a pre-chosen rate (e.g., 10 to 100^{o} C/min). Excursions in sample temperature due to sample response to heating are recognized by using a second sample holder with an inert sample and a second thermocouple. The second sample holder is in the same heater environment as the first one. The thermocouples are connected in opposition to each other, so that the net output indicates the <u>difference</u> in temperature of the control sample and the test sample. The experiment requires that the heating rate be kept low so that all parts of the two sample holders will be in thermal

equilibrium except for the small difference due to test sample response. The test sample decomposes over a period of many minutes, and is ordinarily completely decomposed (or vaporized) by the time the temperature reaches 450-500^{o} C (typical for tests on ammonium perchlorate). Exothermic samples must be sufficiently dilute to avoid runaway self-heating. Otherwise, rapid evolution of gases disrupts the sample and effectively terminates the test. The sample holder is heated in an inert atmosphere when atmospheric effects are of concern. Very little experimentation with propellant ingredients has been done at pressures above one atmosphere.

Figure 4.1 shows a typical DTA record from a test on ammonium perchlorate. From this and other tests, it is known that AP decomposes slowly by dissociative sublimation at temperatures of 220-242^{o} C and experiences an endothermic crystal phase change at 242^{o} C. At higher temperature, more complex exothermic decomposition occurs. DTA tests typically show double maxima in the exotherm, centering on 370^{o} C and 490^{o} C. Details are dependent on experimental methods, and the reason for the double peak is not unambiguously established. Other decomposition experiments (e.g., involving analysis of gas evolved during heating) help to clarify what is happening in decomposition experiments (e.g., it is generally agreed that AP decomposes by dissociative sublimation, decomposition of the $HClO_4$ product, and successive reactions that oxidize the primary NH_3 product. Since the secondary reactions are likely to be in the gas phase, their progress depends on pressure, dilution by other gases, presence of container walls, and temperature-time history in the reaction volume. The only ingredient experiment with AP where these conditions approximate those in a propellant combustion zone is in self-deflagration of pure AP samples (Ref. 4.2, 4.3).

In varying degree according to the specific ingredient under consideration, it is appropriate to regard the usual decomposition experiments only as a starting point for any postulate regarding how decompositon proceeds during combustion, keeping in mind that most of the reaction that takes place during combustion (including most of the transformation from solid to gas) occurs at temperatures much higher than in the controlled decomposition experiments (Ref. 4.4, 4.5). With this mental reservation as a guide, the

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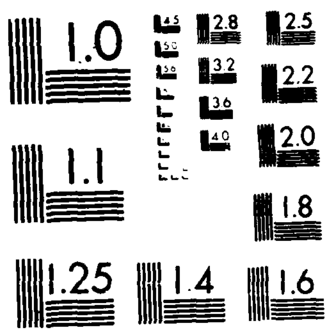

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following is a description of ingredient decomposition with emphasis on what is, or is not, known about high temperature decomposition.

<u>Crystalline Oxidizers</u>. In most propellants, 40-90% of the mass is in the form of crystalline particles of oxidizer. The more chemically stable of these (e.g., potassium perchlorate and ammonium nitrate) decompose endothermally, will not deflagrate on their own at rocket motor pressures, and are little used because their propellants yield relatively low specific impulse. Interestingly enough, these propellants have also not exhibited oscillatory combustion. Table 4.1 shows estimates of significant tempertures for response of various ingredients. The melting temperature of AN is about ___^{o} C (KP apparently decomposes without melting). Decomposition starts at about ____^{o} C for KP and _____^{o} C for AN in DTA tests. It is generally believed that the surface of a burning propellant AN is molten, raising the possibility of liquid phase mixing with other ingredients (or flow over their surface). The primary decomposition step of AN is apparently to _____ and ______. There is little data on surface temperature during burning. The decomposing surface of KP in the combustion of propellants is apparently dry, with the primary decomposition step being to _____ and ______ vapor. A molten decompositon product (KCl) is sometimes left on the KP surface during some decomposition experiments.

A variety of exothermic oxidizers have been considered for propellants. The most common is AP, which was discussed as an illustrative example earlier. The nitramines (particularly HMX) have also been used extensively. These materials are "energetic", will self-deflagrate, and the nitramines are sensitive and detonatable. The decomposition characteristics are summarized in Table 4.1. It was long believed that AP decomposed by dissociative sublimation, as observed in many controlled heating experiments (where AP deposited out on cold surfaces of low pressure reactors). Exothermic steps were thus assumed to occur in the gas phase, with the surface efflux being NH_3 and $HClO_4$. Early investigators found that AP would self-deflagrate at elevated pressure, but continued to argue that deflagration was supported by an $HClO_4$-NH_3 flame. Studies in the 1960s showed that at usual rocket motor pressures above 2MPa (and below about 10 MPa), AP deflagrated with a frothy

surface (Ref. 4.2). It was also noted that the observed burning rates were hard to explain in terms of exothermic reactions in the gas phase only (Ref. 4.6), and it is now argued that roughly 50% of the heat release occurs in a decomposing liquid surface layer. The temperature of this layer has been estimated to be around 600° C (Ref. 4.7), well above the temperatures of conventional controlled decomposition experiments. The details of this complex high temperature decomposition process are still matters of speculation, as is the even more exotic decomposition behavior observed at higher pressures (15 - 30 MPa, Ref. 4.8). Dissociative sublimation may be the relevant process in low pressure propellant combustion. In fact, the low pressure limit for self-deflagration may be due to "loss of" the surface liquid and its exothermic steps as pressure decreases (Re. 4.9). The total heat release by self-deflagration is low by propellant standards, while the self-deflagration rate is comparable to propellant rates (at 7 MPa), suggesting that a significant part of the heat release is at the surface; rate is observed to drop off rapidly with decreasing pressure, consistent with an interpretation that the portion of heat release at the surface decreases with pressure (corresponding to decreasing surface temperature). It may be that the low pressure deflagration limit is due to decrease of the surface temperature to an as yet unproven AP melting temperature and shut down of all exothermic surface reaction. Important to later discussion is the point that, whatever the cause of the low pressure limit, it is much higher when the initial (bulk) sample temperature is low (Ref. 4.__). This further illustrates the marginality of the self-deflagration, reflecting a "marginality" of the heat balance resulting from the low final flame temperature of AP (estimated to be only 1400° C for ambient sample temperature.

The details of AP decomposition and self-deflagration have been pursued in detail here because there is far more information pertaining to AP than any other oxidizer, and because the results demonstrate the limitations of controlled heating decomposition experiments in determining decomposition behavior in combustion waves. Thus, it is not clear where one should obtain the kinetic and transport properties that are called for in analytical models of propellant combustion, and the reader should anticipate that such properties

as activation energies, molecular weights and diffusion coefficients in analytical models may often be treated as undetermined parameters, with values chosen to yield best correlation of global combustion characteristics such as burning rate. This is common practice in combustion science, where measurement of global combustion behavior is often easier to do than is measurement of more fundamental aspects of the process. It is also appropriate to note that validity of this approach rests on the relevance of the particular analytical model to the real combustion process.

Returning to the other energetic oxidizer, the DTAs for HMX and RDX are shown in Fig. 4.2. Decomposition proceeds at a low rate prior to melting. The melt endotherm is evident in the DTA (- 220° C for HMX, 200° C for RDX). Decomposition is already proceeding slowly at these temperatures, and the width of the melt endotherm is deemed by some investigators to reflect something more complicated than mere phase change. The melting endotherm is followed immediately by an exotherm for RDX and, in controlled heating experiments, the sample size and dilution must be chosen to prevent abrupt consumption of the sample due to self heating (i.e., loss of control of sample temperature). The exotherm for HMX occurs at higher temperature, around 275° C. Details of the exotherm are generally a function of experimental technique, test pressure, heating rate, sample particle size, etc. Methods have been devised to calculate order and activation energy of decomposition reactions from the thermal analysis tests such as DTA, DSC and TGA,* but the results for HMX and RDX depend upon method and experimental variables. Perhaps more significant, the test samples are ordinarily fully consumed long before reaching the temperature deemed to prevail on the surface of a burning sample, and the decomposition rates are such that during deflagration very little reaction would occur in the short time spent in the combustion wave at those temperatures experienced in controlled decomposition tests. Thus it is uncertain whether decomposition data obtained in controlled heating experiments is relevant to combustion. The results do indicate that a decomposing melt would be expected on a burning surface.

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* DTA means "differential thermal analysis", DSC means "differential scanning calorimetry", and TGA means "thermal gravimetric analysis", which is time-resolved weight measurement during heating.

Both HMX and RDX are nearly stoichiometric in composition, in the sense that most of the carbon and hydrogen atoms are oxidized to CO_2 and H_2O in the final deflagration reaction products. The energy release is correspondingly high, and HMX and RDX self deflagrate over a wide range of conditions, with flame temperatures around ____^{o} C (compared to around 1400^{o} C for AP). The self-deflagration rates are about 1.2 cm/sec at 7 MPa (HMX), as compared to a value for AP of about 0.7 cm/sec. HMX and RDX burn with an exothermic reaction zone in, and immediately above the surface that leads to temperatures around ___^{o} C, with a second flame that stands far enough from the surface (Fig. 4.3) to have relatively little effect on self-deflagration rate (a behavior to be noted below also for double base NC/NG propellants). The surface temperatures of deflagrating HMX and RDX appear to be lower than those of AP in spite of their higher self-deflagration rate, indicating that they decompose relatively easily. The melt layer on the surface is relatively more thick than for AP, raising the possibility of some liquid phase mixing with fuel melts in a propellant situation.

<u>Binders</u>. Propellants are held together by plastic-like binder materials, which are the <u>connected</u> part of the propellant matrix. Binders are also the fuel ingredient. They range in practice from hydrocarbon polymers, such as PBAN and HTPB, to polymers with energetic plasticizers, such as _____ and _____, to energetic polymers or colloids, such as NC/NG ("double base" binders). Propellants with energetic binders typically have a lower volumetric loading of oxidizer because the binder has more oxygen content, and because energetic binders are usually less suitable to high solids content from the standpoint of processing, mechanical properties, and hazard.

The typical hydrocarbon elastomeric binders decompose endothermally in controlled heating experiments in the temperature range ____ to _____^{o} C. There seems to have been very little study of the vapor species that result under rocket motor-like conditions. It is recognized that the initial mode of decomposition of a polymer molecule will involve bond-breaking in the polymer backbone in some polymers (e.g., __________), and breaking of bonds to pendant groups in other polymers (e.g., __________). In the controlled heating

experiments, most of the hydrocarbon polymers soften to viscous "melts" in the ______ to _____ ^{o} C range and bubble at from ________ to _____ ^{o} C, with this temperature differing significantly for different polymers. In slow heating experiments, most of the test sample is decomposed by the time the temperature reaches ___ ^{o} C (a sample DTA curve is shown in Fig. 4.4). The semi-liquid surface is observed also in combustion experiments, and residual evidence of a melt remains on the surface of propellant samples quenched from high pressure burning. In combustion modeling, it would be useful if the binder response to heating could be characterized by a one-step irreversible conversion to vapor products according to an Arhenius rate law. The available information suggests that pressure is more complicated, and that a search for appropriate values of activation energy and pre-exponential factors for the rate law is of limited meaning.

Of the energetic binders, the nitrocellulose-nitroglycerin system has been the most studied. This energetic binder has been used as a monopropellant for the last 100 years, first as a gun propellant and then as the first satisfactory rocket propellant. At the molecular level it consists of two ingredients, NC and NG. In decomposition of the colloid, NG apparently evaporates in the ____ to ____ ^{o} C range, and NC decomposition becomes important at ____ ^{o} C.

Decomposition of NC is reported to start with rupture of $O-NO_2$ bonds, and the activation energies obtained in some experiments are consistent with this. However, the initial reactions are in the condensed phase, as are some subsequent steps, and the rate of conversion to gas depends on this complex sequence of reactions and evaporation. When NG or other plasticizers are present, the reacting surface layer includes the evaporating plasticizer and the surface thus is a complex mixture of ingredients and intermediate products in a solution or froth. The NC decomposition is autocatalytic and exothermic, with its rate often strongly affected by additives used to either inhibit the autocatalytic reaction (for storage stability) or enhance reaction rates at elevated temperature to increase burning rate. During self-deflagration, the surface regression rate of different double base formulations are found to linearly dependent on the heat of reaction (Fig. 4.5), which can be varied by

changing NC/NG ratio or by changing the degree of nitration of the NC. This correlation is believed to be due to the dominance of exothermicity of the reactions in the condensed phase-melt-foam layer, and the effect of composition variables on these exothermic reactions. Indeed, considerable success has also been achieved in modification of burning rate by catalysts that are thought to affect these reactions. The surface temperatures of self-deflagrating double base formulations are reported to be 320-400° C, with considerable uncertainty associated with the absence of a well defined and unambiguously located surface due to gas formation "in" the condensed phase. Temperatures determined by thermocouples traversed by the combustion zone show a very steep temperature rise (Fig. 4.6) to about ___$^\circ$ C in the gas phase, indicating exothermic gas phase reaction. After a further, more gradual temperature rise, a second steep temperature rise occurs to a final temperature of ___ to ___$^\circ$ C. The second steep temperature rise corresponds to a flame that is readily visible in experiments below 1.0 MPa. In fact, the flame stand-off distance is sometimes reported as a function of pressure (Fig. 4.7). While a large part of the heat of reaction is released in this stand-off flame, it is too distanct from the surface to be a dominant factor in heat flow to the solid preheat region, except possibly through its effect on reaction rate in the primary exothermic region. However, the stand-off flame may be important to the transient combustion response, and to combustion of other ingredients when the propellant is used as a binder in composite propellants.

Metals. The principal metal ingredient in current propellants is aluminum powder. While there is no decomposition or deflagration to relate to the present section title, it is important to note that most metals don't vaporize at the temperatures of the propellant burning surface, posing the questions of how the metal particles get away from the burning surface and where they burn. Since the particles emerge at the burning surface from a binder-surrounded matrix location, they are often in an adherent binder melt. It is observed that metal particles concentrate to some extent on the surface (as do other additives, such as particulate burning rate catalysts). Aluminum particles are resistant to ignition because of a refractory Al_2O_3 coating on the particles.

Combustion ordinarily takes place after detachment from the surface, often as agglomerates of large numbers of particles that were concentrated on the burning surface. Details will be discussed in the next section, but it should be kept in mind that metals (and all nonvolatile ingredients or intermediate reaction products) experience a complex concentration-agglomeration-sometimes ignition process on the burning surface that is strongly dependent on other propellant variables and on pressure. This process is responsive in its own unique way to flow oscillations and associated oscillations in other combustion zone processes.

4.4 General Features of Propellant Combustion

In preparation for discussion of oscillatory combustion, it is necessary to first understand the nature of the combustion zone and processes that oscillate. Adopting the view of small perturbation theory, we may look upon the combustion as a process oscillating about its mean state, which is the steady state part of a transient solution of a nonsteady problem. From the discussion of ingredient decomposition and self-deflagration, we can anticipate that the combustion zone can be very complex for heterogeneous propellants, that the nature of the combustion will be very different with different ingredient combinations, and that the details (both physical and chemical) will be only qualitatively known and difficult to measure. On the other hand, this has not stopped efforts to model the combustion behavior analytically, both steady and nonsteady. While such modeling may at times seem futile, given the degree of oversimplification necessary, it is an essential part of development of physical insight, provides a basis for ordering and interpreting experimental results, and provides a necessary part of any model of the overall combustion behavior that determines whether oscillations will or will not occur and how they may grow.

The goal of this section is to provide some perspective on what the combustion zone is. We may start with a one-dimensional view as in Fig. 4.8., and then examine what processes (one-dimensional or otherwise) may be going on in each region of the one-dimensional picture. For convenience, the regions

will be chosen as follows (Fig. 4.8), with more detailed description following a preliminary identification.

1. A thermal induction region where reactants are heated by conduction, but where significant chemical reaction is not present.
2. A second thermal induction region where chemical reactions are important but no disruption of the microstructure has yet occurred.
3. A region where liquification or vaporization of some ingredients causes breakdown of the heterogeneous microstruction, and an opportunity for diffusion of ingredients and/or intermediate decomposition products.
4. A "surface", below which most of the material is condensed phase, and above which most of the material is vapor phase.
5. A primary gas phase induction zone, in which exothermic reaction is delayed for some propellants) while ingredient mixing occurs and build-up of free radical concentration sets the stage for Region 6 flames. For some propellants (double base, some nitramine) this region involves a continuation of Region 3 exothermic reactions.
6. A primary gas phase flame (or flamelets) that is closely coupled to the underlying regions by virtue of its proximity and heat release. Such a flame is viewed as yielding intermediate reaction products capable of further reaction (homogeneous propellant), or as consuming some portion of reactants that have already mixed (heterogeneous propellants).
7. In the case of homogeneous propellants, there is usually a further chemical induction region prior to a secondary flame. With a heterogeneous propellant, this region may instead consist of a myriad of diffusion-controller oxidizer-fuel flamelets, and may at the same time have chemical induction processes leading to secondary monopropellant flames if the diffusion or reaction of adjoining ingredient vapor flows is slow.
8. It is customary to specify a secondary exothermic flame, which is clearly evident in the case of most homogeneous propellants. With heterogeneous propellants (as implied in (7)), there are usually

exothermic reactions extending well above the primary flame, which may or may not appear as a well-defined secondary flame, depending on the rate of diffusive mixing of ingredient vapors and the chemistry of their interaction.

9. Finally, relatively nonvolatile ingredients, such as metals, may remain substantially unvaporized at the secondary flame, and burn as a cloud of individual particles (droplets) while moving outward in the product flow.

Region 1 is the leading front of the thermal wave, in which heat conduction is the primary process. For propellants with very fine ingredient particles, the propellant may behave as a homogeneous material. For particle sizes larger than 50 μm, the heat flow is probably significantly three-dimensional, especially when the thermal properties of the solids are widely different (as they usually are). The heat-up may also involve crystal phase transitions and thermal properties that are temperature-dependent. These considerations may be important in determining the non-one-dimensional features of overlying regions, but are rarely considered in analytical models.

Region 2 is similar to Region 2 in the sense that physical degradation has not proceeded to the point of facilitating diffusion of ingredients, but differs from Region 1 in the presence of chemical reactions. In a homogeneous propellant, this would correspond to beginning of decomposition, and the processes involved may sometimes be the ones affected by burning rate catalysts. In a heterogeneous propellant, this region may have either interfacial reactions between ingredients, or beginning decomposition of the less stable ingredients. In many one-dimensional models this region encompasses all of the condensed phase reactions because those models do not allow a Region 3 for bubble formation or diffusion of ingredients in the condensed phase.

Region 3 is intended to encompass a variety of complex situations that are acknowledged to be important but usually neglected or represented artificially in analytical models. These are processes associated with phase change to liquid and/or gas. The energetics of such processes are often included in models as either homogeneous or surface heat absorption (phase change) or

release (reaction). Analytical models rarely address the three-dimensional realities of growing bubbles; interfacial reactions between "melting" ingredients; subsurface decomposition of one ingredient in the matrix of another, more thermally stable ingredient; or interdiffusion of one molten reactant into another. There are practical situations where one might expect each of these processes to be important. Some examples are the following:

1. AP-hydrocarbon binder propellants exhibit burning down the contact surfaces between oxidizer and binder when burning at pressures near or below one atmosphere, resulting in a Region 3 consisting of solid oxidizer, solid binder, penetrated by exothermally reacting interfaces in which as yet undetermined ingredient interaction-reaction processes release heat. At higher pressure the interface seems to be nonreactive, the binder exhibits a melt surface, and the AP self-deflagrates.
2. Various theories for combustion of HMX-HC binder propellants have been proposed, one of which (Ref. 4.___) has individual HMX particles burning ahead of the unreacted matrix, such that Region 3 would have a population of exothermic sites moving sporadically inward with hot gas and flow. Another source suggests (Ref. 4.___) that the HMX and the binder melt and mix on the surface and burn as a homogeneous surface layer, in which case Region 3 would be a melt-mixing region with possible bubble formulation. The apparently contradictory descriptions are probably related to real differences in behavior over the range of formulations and test pressures used.
3. Double base (NC/NL) propellants are usually relatively homogeneous, but the "leading edge" of the reaction wave quickly generates gaseous products, and Region 3 is an exothermic layer commonly called the "foam" zone (Ref. 4.__, 4.__). The undecomposed material softens to a viscous fluid, presumably populated by growing microbubbles. Near the surface, continued degradation of the melt is reported to leave a concentration of carbonaceous solid residue, which figures in arguments on how catalysts change burning rate (Ref. 4.__).

This diversity of behavior in Region 3 is belabored here because its importance to combustion behavior is widely acknowledged, but rarely embraced

realistically in analytical models of combustion (partly because it would greatly complicate analyses, and partly because the processes are so difficult to measure that good guidance for modeling is lacking).

Region 4 is ideally defined as the "burning surface", the interface between condensed and gas phase. In a one-dimensional model it is a plane that can be characterized by a single temperature and regression rate. Combustion models ordinarily treat the combustion zone as made up of a condensed phase region and a gas phase region, with appropriate (but different) conservation equations for each region. Boundary conditions are matched at the "surface". this gives the surface a singular role in the analysis, and measured or calculated surface temperatures are conspicuous in discussions of theory. From the comments about Region 3, it is evident that the "surface" is almost never a plane with uniform state. Even the self-deflagration of a pure ammonium perchlorate crystal does not give a uniform planar surface (Fig. 4.9a), and surfaces of propellants are notable for their complex structure soon after they are extinguished and have time to release bubbles and settle down before freezing (Fig. 4.9b, c). It may be anticipated that the surface complexity implied by Region 3 will remain neglected in analytical models (especially nonsteady models), but notable efforts have been made to deal with specific aspects of such "non-ideal" behavior (Ref. 4.__ to 4.__) in cases where representation of such complications was considered crucial to useful modeling.

The nature of Region 5 is strongly dependent on the kind of propellant. With double base propellant (and pure HMX) this is a thin region in which continued exothermic reaction occurs (Fig. 4.6), effectively supplying heat to the underlying regions. In these systems, the temperature that is reached represents about 50-6% of the total heat release. The reaction products of this region are sufficiently stable so that further heat release is delayed to a more remote Region 8 of the combustion zone.

With AP propellants, Region 5 is an induction region of low heat release. Over areas of AP, this is a stand-off region (Fig. 4.10) for the AP monopropellant flame,* and is so thin (10 - 20 μm, Ref. 4.__, 4.__) that it has

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* The AP flamelet may be absent at low pressures, or with very small AP particles.

not been directly observed. Over and near areas of surface binder, Region 5 is a mixing region for oxidizer and fuel, a stand-off region for the O-F flame. Thus, with AP propellants, Region 5 is one of low heat release, culminating in AP and O-F flamelets. Being a thin region over a convoluted surface, it is not particularly visible.

Region 6 is defined here to accommodate the near-surface flames that occur with AP propellants. Over areas of AP, this corresponds to the AP self-deflagration flame noted above and described in Section 4.3. This region also accommodates primary O-F flamelets noted above (Fig. 4.10) that consume the oxidizer and fuel vapors that have mixed in Region 5. These flamelets are the leading edge of more extended diffusion flamelets in the mixing region remaining beyond Region 6. They are distinct from the extended flame in that they represent a near-surface concentrated combustion of oxidizer and fuel vapors premixed without reaction in Region 5. In addition, the primary flamelets in Region 6 are the flame holders for the more extended outer diffusion flamelets in Region 7, and their presence, position and heat release depend on a delicate balance of diffusion of species and heat, and of reaction kinetics for the oxidizer-fuel mixture.

The primary O-F flamelets described above may be important with other heterogeneous systems, such as potassium perchlorate oxidized systems, but detailed studies are lacking. Current nitramine composite systems differ in that O-F vapor mixing does not set the stage for exothermic flamelets (because the nitramines are already stoichiometric).

Region 7 is a chemical induction region for many propellants, such as double base and some nitramine composite propellants. The region contains decomposition products such as NO, H_2, CO and CO_2, which eventually react to N_2CO, CO_2 and H_2O in an outer flame (Region 8). The thickness of Region 7 for these propellants is strongly pressure-dependent (Fig. 4.3). The temperature is roughly ___ ^{o} C. Because of this induction region, the high temperature outer flame does not contribute strongly to propellant burning rate. However, the pressure dependence of chemical induction processes probably makes the outer flame contribution more important at higher pressure, resulting in a relatively high dependence of steady state burning rate on pressure for those types of propellants. As will be seen later, this pressure dependence is a

factor in the dynamic response to oscillations, but not the decisive contribution one might first suspect.

In composite propellants, Region 7 is one of continued diffusion of oxidizer and fuel vapors. Unlike the underlying regions, the temperature here is high enough to yield chemical reaction rates that are high compared to the diffusion rates. As a result, the reactions are concentrated in the mixing boundaries between microscopic outward moving oxidizer and fuel flows from the heterogeneous surface, yielding flamelets in these microscopic mixing fans (Fig. 4.10). Region 7 is thus populated by microscopic O-F flamelets, anchored to the primary flamelets in Region 6. The height of this region is dependent on the size of the heterogeneous surface elements (and corresponding mixing lengths in the diffusion field). In the case of AP propellants, the substantial heat release in these O-F flamelets and the moderate distance from the surface lead to a significant contribution to burning rate, larger when particle size is small. The pressure dependence of this contribution to burning rate is relatively low, because the diffusion-limited flamelet height is relatively insensitive to pressure. In the case of nitramine composite propellants, the O-F reaction is not energetic and, consequently, contributes little to heat flow to the surface and to the burning rate. In addition, the nitramine product flow may consist of only intermediate reaction products and Region 7 may still be a chemical induction zone followed by a high temperature secondary flame in Region 8. Details depend strongly on nitramine particle size, pressure, and type of binder.

Metal ingredients become fully inflamed in Region 7 with AP propellants, but are probably not yet up to speed with the gas flow and are still largely unburned. With double-base and nitramine propellants, complete inflamation of accumulations of aluminum is often delayed until entry into the high temperature of Region 8.

Region 8 is assigned here to the relatively concentrated stand-off flame following chemical induction and non-exothermic mixing in Region 7. The chemical induction-secondary flame process is moderately well understood in double base propellant combustion (Ref. 4.___, 4.___) and nitramine self-deflagration (Ref. 4.___), but its nature is more diverse and less well characterized for nitramine composite propellants because of the involvement of

both surface and gas phase mixing of ingredients and product flows (Ref. 4.___, 4.___). However, it is clear that a stand-off secondary flame, similar to that with double base propellants, occurs with some nitramine composite propellants under some conditions (Ref. 4.___). This implies that the binder vapors can mix with the primary or intermediate vapor products of the nitramine without forming the diffusion flamelets characteristic of AP composites. The secondary flame in such cases is more nearly a pre-mixed, planar flame in Region 8.

Region 9 is defined here to accommodate the continued combustion on nonvolatile reactants, such as metals, and intermediate products, such as carbon, that survive Regions 3 - 8 unreacted. In some propellants, a significant part of the heat release occurs in an extended region, which can include the entire volume of a small or low pressure motor. This is highly dependent on the details of the concentration-agglomeration of the reactants in Regions 3 and 4 (Ref. 4.___), processes that determine size of the slow-burning agglomerates in Region 9. It is also important to realize that the reaction products of aluminum combustion are Al_2O_3 droplets, which may constitute up to 40% of the reaction products. This can be the dominant source of damping of gas oscillations.

From the foregoing, it is evident that the character of the combustion zone can be quite different with different combinations of ingredients, particle sizes, and pressure of the combustion environment. Detailed understanding of the combustion processes is only qualitative and not well catalogued. Qualitative aspects are fairly well understood for double base propellants and AP composite propellants. The description presented above, in the context of Fig. 4.8, is contrived to fit a one-dimensional picture, partly as a means to address a complex and diverse array of substantially sequential processes, and partly to provide the framework for the one-dimensional models that are used to analyze combustion. It is important to understand that the gas flow in the combustion of a motor is not one-dimensional (sometimes the flow is modeled one-dimensionally, but, when it is, the dimension chosen is perpendicular to the dimension pictured in the combustion zone in Fig. 4.8). In other words, the combustor flow is usually parallel to the burning surface and may exert a shearing effect on a combustion zone such as that pictured in Fig. 4.8 - 4.10. This gives rise to the burning rate enhancement known as

"erosive burning" in steady state and implies that the combustion zone is not the same under sheared flow conditions as it is when flow is simply outward from the surface. In oscillatory combustion, one should expect two kinds of effects from parallel flow:

a) The combustion zone that is oscillatory differs according to the mean flow situation (and hence the location in the combustor and time during charge burning).

b) The gas oscillations will normally involve components of motion parallel to the burning surface so that the combustion zone experiences three-dimensional oscillations (the nature of which depend on location in the combustor and on the acoustic mode of the oscillation).

This situation will be addressed at length in this book, but it should be recognized at the outset that we are examining the interaction between a very complex combustion process and a very complex gas motion. Only if one understands the complexity of the real processes can one understand the degree of, or reason for, simplification used in analytical models, or recognize the limitations in their use and the needs for better experimentations, analysis and theory.

Chapter 4 - Figure Legends

Fig. 4.1 Sample differential thermal analysis record of ammonium perchlorate (heating rate ___^{o} C/sec)

Fig. 4.2 Sample DTAs for HMX and RDX (heating rate ___^{o} C/sec)

Fig. 4.3 Stand-off distance of secondary flame for HMX self-deflagration (Ref. 4.___) (measured from combustion photography).

Fig. 4.4 DTA records for typical hydrocarbon binders.

Fig. 4.5 Dependence of the burning rate of double base (NC/NG) propellants on heat of reaction.

Fig. 4.6 Temperature profile in the combustion wave of an NC/NG propellant burning at ___ MPa. Steep temperature gradient immediately above the surface indicates an exothermic reaction region. Low gradient further out indicates region of low heat release preceding secondary flame.

Fig. 4.8 Regions of the combustion wave (chosen as a framework for description of combustion zone processes). Curve on the right shows a temperature profile illustrative of burning at about 7 MPa.

Fig. 4.9 Surfaces of samples quenched by rapid depressurization:

a) AP crystal burned at _____ MPa,
b) nonaluminized AP/PBAN propellant burned at ___ MPa, and
c) aluminized AP/PBAN propellant burned at ___ MPa.

Fig. 4.10 Sketch of flame complex for AP/HC binder propellant:

a) near-surface flamelets, and
b) extended diffusion flames.

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